NASA/CR—2003-212331

Commercial Aircraft Emission Scenario for 2020: Database Development and Analysis

Donald J. Sutkus, Jr., Steven L. Baughcum, and Douglas P. DuBois
Boeing Commercial Airplane Group, Seattle, Washington

May 2003

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Prepared under Contract NAS3–01140, Task 5

National Aeronautics and
Space Administration

Glenn Research Center

May 2003

This report contains preliminary findings, subject to revision as analysis proceeds.

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Executive Summary

This report describes the development of three-dimensional inventories of aircraft fuel use and emissions (NOx, CO, and hydrocarbons) from commercial air traffic projected to the year 2020. The data are on a 1° latitude x 1° longitude x 1 km altitude grid. This emission scenario was developed for the NASA Ultra Efficient Engine Technology (UEET) Program under contract NAS3-01140, Task Assignment 5. It will be available for use by atmospheric scientists conducting modeling studies on the atmospheric effects of aviation, including the NASA Global Modeling Initiative (GMI).

Emissions produced by the world's entire aircraft fleet come from scheduled, charter, military, and general aviation air traffic. In this report, we present the results and methodology used for the calculation of emissions from commercial air traffic which includes both the scheduled and charter portions of flight operations by turboprop, passenger jet, and cargo jet aircraft.

Annual fuel use for 2020 by commercial air traffic is projected to be 3.47×10^{11} kilograms. This is 2.6 times the estimated fuel use by 1999 commercial air traffic. Global NOx emissions by commercial air traffic are projected to be 4.89×10^{9} kilograms (as NO_2), which is approximately 2.8 times the estimated 1999 NOx levels. For comparison, total revenue passenger kilometers are projected to increase from 3,170 billion in 1999 to 8,390 billion in 2020, which is an increase of a factor of 2.65. The 2020 scenario includes charter air traffic while the 1999 inventory (Sutkus and co-workers, NASA CR-2001-211216) only included scheduled flights that were listed in the Official Airline Guide (OAG).

The 3-dimensional commercial aircraft emission scenario of fuel use and emissions for the year 2020 has been delivered in electronic format to the NASA Glenn Research Center.

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Glossary

ANCAT	Abatement of Nuisances Caused by Air Transport, a study group of the European Civil Aviation Conference
ASK	Available seat kilometer (the number of seats an airline provides times the number of kilometers they are flown)
BMAP	Boeing Mission Analysis Process
CAEP	ICAO Committee on Aviation Environmental Protection
CIS	States of the former Soviet Union
CMO	“Current Market Outlook” - forecast of air traffic demand and airplane fleets published yearly by Boeing
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DOT	United States Department of Transportation
DLR	Deutsches Zentrum für Luft- und Raumfahrt
EI(CO)	Emission Index (grams CO/kg fuel burn)
EI(HC)	Emission Index (grams hydrocarbon/kg fuel burn)
EI(NOx)	Emission Index (grams NOx (as NO_2)/kg fuel burn)
GAEC	Global Atmospheric Emissions Code
HC	Unburned hydrocarbons
H_2O	Water
ICAO	International Civil Aviation Organization
kg	kilogram
lb	pound
Load Factor	Percentage of an airplane's seat capacity occupied by passengers on a given flight
NASA	National Aeronautics and Space Administration
NOx	Oxides of nitrogen (NO + NO_2) in units of gram equivalent NO_2
OAG	Official Airline Guide
OEW	Operating Empty Weight
SO_2	Sulfur dioxide
TOGW	Takeoff gross weight
U.S.	United States
3-D	Three-dimensional

1. Introduction

The NASA Ultra Efficient Engine Technology (UEET) program was initiated to promote the development of fuel efficient and low-NOx emissions jet engines for the future and to evaluate the effects of aircraft emissions on the atmosphere and human health. The work described here was done in support of the UEET program Environmental Impact Assessment Element (WBS 1.2) that includes atmospheric modeling, health risk assessment, and emission characterization work. The creation of future global emission scenarios for the commercial aircraft fleet as a function of altitude and geographical position (referred to as “3-D emission scenarios”) is an important component of the atmospheric modeling portion of this element. These scenarios are used as the input to chemical transport models to evaluate the effect of aircraft emissions: how long they persist in the atmosphere, how much they perturb the chemistry or microphysics of the upper troposphere, and how they compare with other sources of NOx, water, soot, and condensation nuclei in the upper troposphere.

In previous NASA studies funded under the High Speed Research, Advanced Subsonic Technology and Ultra Efficient Engine Technology programs, we have developed 3-D emission inventories for aircraft fleets for 1976, 1984, 1992 and 1999 (Baughcum *et al.,* 1996a and 1996b and Sutkus *et al*., 2001) and have created 3-D emission scenarios of both subsonic and supersonic traffic for 2015 (Baughcum *et al*., 1998; Baughcum and Henderson, 1998). ANCAT and DLR have also published historical 3-D emission inventories and projections for 2015 (Schmitt and Brunner, 1997; Gardner, 1998). The emission scenario work of NASA, ANCAT and DLR has been compared and contrasted in the *Intergovernmental Panel on Climate Change Special Report on Aviation and the Global Atmosphere* (Henderson *et al*., 1999).

The NASA-funded work as well as that of ANCAT and DLR has used a "bottom-up" approach in which aircraft flight schedules are obtained or estimated and the aircraft/engine combinations in these schedules are identified. Detailed calculations of fuel use and emissions are then made along each flight path and the results are distributed over a 3-dimensional global grid space.

Emissions produced by the world’s entire aircraft fleet come from scheduled, charter, military and general aviation air traffic. In this report, we present the results and methodology used for the calculation of emissions from projected year 2020 commercial air traffic. Commercial air traffic includes both the scheduled and charter portions of flight operations by turboprop, passenger jet, and cargo jet aircraft. The flight schedule used for this work is based on future traffic projections from the Boeing 2001 Current Market Outlook (CMO) and the year 2000 Official Airline Guide (OAG) city-pair flight schedule. The OAG accurately accounts for scheduled passenger and freighter flights in most regions of the world. The Current Market Outlook traffic flows are used to scale the 2000 OAG city pair schedule to generate the 2020 schedule by city pair. This 2020 schedule reflects the OAG city pairs identified as of the year 2000, the assumption being that air travel patterns in 2020 will resemble those in 2000. The regions where this might not be the case are the People's Republic of China and the states of the former Soviet Union, where city pair networks continue to evolve.

This report documents an emission scenario for only 2020 commercial air traffic (which includes scheduled and charter aircraft). In order for a complete emission scenario for the world's entire 2020 aircraft fleet to be created, the 3-D commercial inventory documented in this work would need to be combined with 2020 3-D scenarios of the military and general aviation components of the world's fleet. Emissions inventories for these other air traffic sectors were developed earlier for 1976, 1984, 1992 and 2015 (Landau *et al*., 1994; Metwally, 1995; Mortlock and Van Alstyne, 1998), but have not been developed for the year 2020.

In order to calculate a commercial aircraft fleet future scenario, projected flight schedule data (number of departures for each city pair along with airplane and engine type) are combined with performance and emissions data to calculate fuel use, oxides of nitrogen (NOx), carbon monoxide (CO), and total hydrocarbons (HC) on a 1° longitude x 1° latitude x 1 kilometer altitude grid. The results for all the different routes and airplane/engine combinations are then summed to produce the total inventory. The details of this process are described in Section 2 of this report.

Results of the 2020 commercial aircraft fleet emission scenario calculations are analyzed and discussed in Section 3 of this report. The results of this calculation are compared to results of the previously published NASA 1992 and 1999 inventory calculations (Baughcum *et al.,* 1996a; Sutkus *et al.*, 2001).

The work described in this report was conducted under NASA Contract NAS3-01140, Task 5. The NASA Glenn Research Center Task Manager was Chowen C. Wey. The principal investigator was Steven L. Baughcum. Terry Higman provided a city-pair level schedule for the 2020 commercial fleet based on the Boeing 2001 CMO. Donald J. Sutkus calculated the 3-dimensional aircraft emission inventories using the Boeing proprietary Global Aircraft Emissions Code (GAEC). Douglas P. DuBois provided guidance on the selection of appropriate performance aircraft and emissions engines characteristics to use when modeling aircraft in the inventories. Steven J. Moskalik and Kyle Kostof provided data to update the aircraft performance database used in the inventory calculations. The GAEC code used to calculate the aircraft emission inventories was written by Peter S. Hertel. The analysis of the results was completed by Steven L. Baughcum, Donald J. Sutkus and

Douglas P. DuBois. General support and document review were provided by Stephen C. Henderson.

2. Scenario Calculation Methodology

2.1 Overview

Figure 2-1 shows a schematic of the process that was used to develop the NASA 2020 global aircraft emission scenario for the commercial aircraft fleet. This process is similar to the one used to create previous NASA global emission inventories and scenarios for the scheduled fleet (Baughcum *et al.*, 1998; Sutkus *et al.*, 2001).

Fleet mix and regional traffic growth projections from the year 2001 Boeing Current Market Outlook (CMO) (Boeing Commercial Airplanes, 2001) were used to create a year 2020 city-pair level flight schedule based on year 2000 Official Airline Guide (OAG) flight schedule data. Performance and emission characteristics were assigned to each aircraft/engine combination in the 2020 schedule based on market and technology projections for aircraft and aircraft engines. A year 2020 3-dimensional global emission inventory was then calculated using the Boeing proprietary Global Atmospheric Emissions Code (GAEC). The details of this process are outlined in the subsections below.

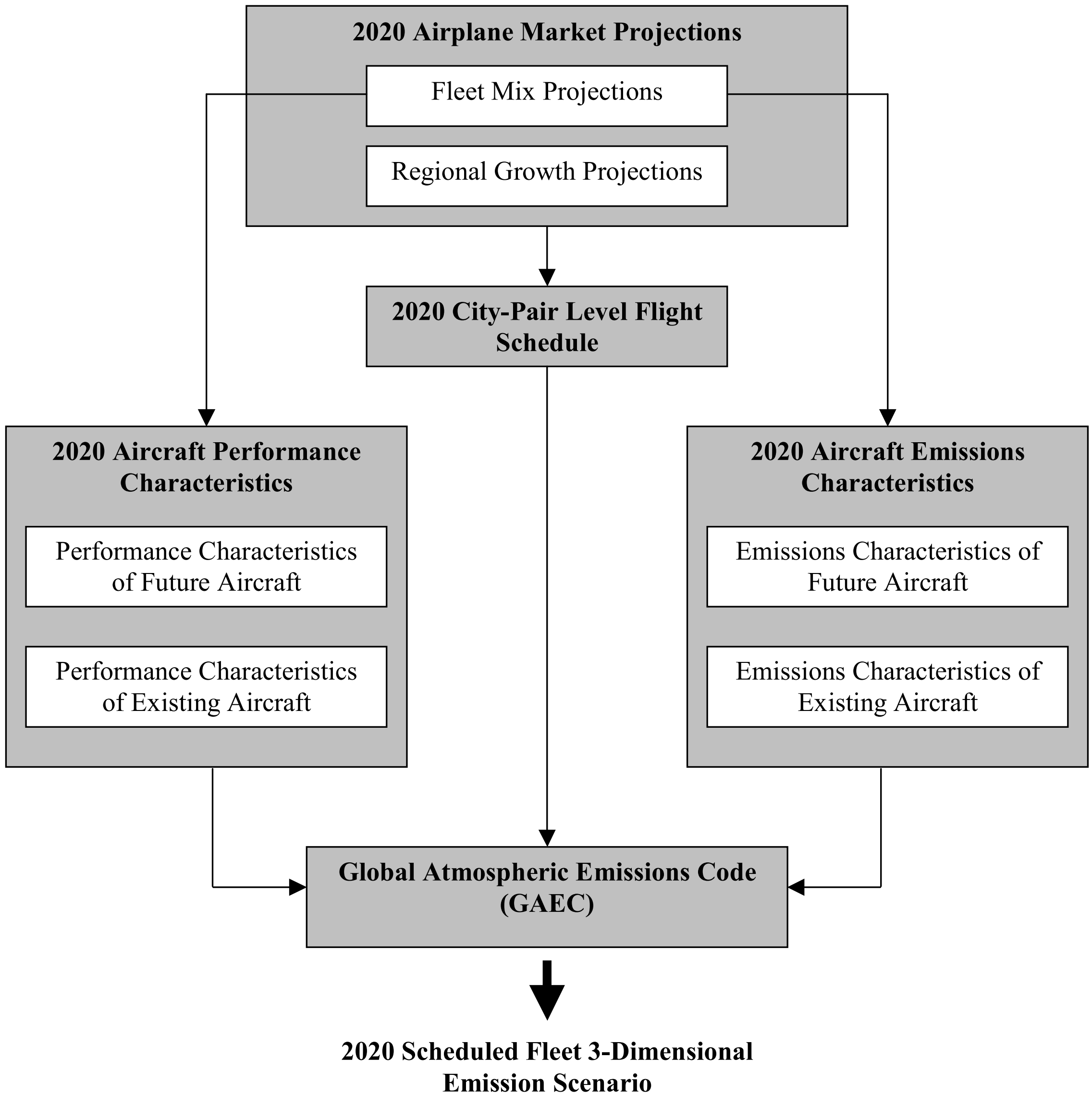

Figure 2-1. Schematic of emission scenario calculation process.

2.2 Schedule Database Development

2.2.1 Market Forecasting

The projected flight schedule used to create the year 2020 emission scenario is based on The Boeing Company's year 2001 Current Market Outlook (CMO) (Boeing, 2001). The CMO is published annually and makes projections of aircraft fleet evolution based upon world economic and aircraft traffic growth projections. The 2001 Current Market Outlook forecasts total traffic demand, which includes scheduled and charter traffic.

> The Boeing year 2001 CMO was published prior to the events of September 11, 2001. These events have brought about significant reductions in the growth of commercial air traffic for the near term. The 2002 Current Market Outlook (Boeing, 2002) predicts a 3% reduction in year 2020 global passenger traffic demand relative to the 2020 traffic demand level predicted in the 2001 CMO that was the basis for the 2020 schedule used in this work.

Two factors determine total air travel growth for a country. The first and more significant factor is economic growth as measured by the increase in the gross domestic product (GDP). For most regions of the world, GDP growth accounts for at least two-thirds of projected air travel growth. The second factor is the value created as airlines reduce prices and increase service offerings and as international trade grows. Over time, this second factor causes the share of GDP that a country devotes to air travel to increase.

Boeing CMO projections of economic and air travel annual growth rates for the 2001 to 2020 time period were made for 42 world traffic flow regions and are summarized by major world region in Table 2-1. Economic growth rates are shown in terms of GDP while air travel growth rates are shown in terms of revenue passenger kilometers (RPK). Detailed air travel annual growth rates for each of the 42 world traffic flow regions are given in Appendix A.

Table 2-1. Gross domestic product and air travel growth rates (in revenue passenger kilometers) by region for the 2001 to 2020 time period.

Region	GDP Annual Growth Rate	RPK Annual Growth Rate
China	6.1%	7.8%
Southwest Asia	5.1%	6.7%
Southeast Asia	4.8%	5.3%
Central America	4.3%	5.4%
South America	4.1%	7.3%
Africa	4.0%	4.8%
Middle East	3.9%	4.2%
Former Soviet Union	3.5%	5.2%
Oceania	2.8%	3.5%
North America	2.8%	3.5%
Europe	2.4%	4.5%
Northeast Asia	2.1%	5.8%
World Total	**3.0%**	**4.7%**

Table 2-1 shows that World GDP is forecast to grow by 3% annually over the next 20 years. In mature economies, such as Europe, Northeast Asia and North America, GDP growth will average between 2% and 3% per year. By contrast, annual GDP growth in developing regions may average well over 4% with China having the fastest GDP growth rate of 6.1% per year.

2.2.2 Aircraft Fleet Size and Mix

Airlines purchase airplanes to fly specific routes as a response to traffic demand. Route characteristics vary by region, so the size mix of airplanes used by the airlines will vary by region. In addition to considering traffic demand growth when making their fleet-addition decisions, airlines also take into account replacement and reallocation of their existing fleets. These projections continuously evolve over time, with airplane sizes, city pairs, and frequencies all subject to change.

There is significant variation among airlines regarding the timing of airplane replacement. Government regulations on noise and emissions also have an effect on retirements. The airplane replacements made in the Boeing CMO forecast were based upon information from airlines whenever possible. Table 2-2 summarizes the guidelines used to remove passenger airplanes from the active commercial fleet when airline information was not available.

Table 2-2. Guidelines assumed for replacement of passenger airplanes in the commercial aircraft fleet.

	Airplanes Designed Before 1980	**Airplanes Designed After 1980**
Single-aisle	25 years	28 years
Twin-aisle	28 years	31 years

For the scenario calculations, unless specific airline information about freighter replacements and extended service lives was available, freighters 35 years old and older not used by package-only carriers (UPS, Federal Express, etc.) were removed from service. For freighters operated by package-only carriers on domestic routes, a 45 to 50 year lifetime was assumed because of the low utilization rates of these airplanes. For all aircraft types, the addition of hushkits was assumed to extend service life by 5 to 10 years.

Airplanes retired from passenger service were re-introduced into the fleet as freighters to satisfy the projected freighter market demand for the particular airplane type. When enough retired passenger airplanes were not available to satisfy the freighter market demand, new freighter aircraft were introduced into the fleet.

The world fleet is expected to more than double by 2020, with total fleet size growing to 32,954 airplanes. Over the 20-year forecast period, 5,053 airplanes are expected to be retired from active commercial service and replaced with new airplanes. An additional 18,406 new airplanes will be needed to fill demand brought about by air traffic growth.

Based upon an estimate of the amount of capacity removed from the world fleet, approximately one-fourth of the market for new commercial jets can be thought of as replacement for older in-service airplanes, and the remaining three-quarters for accommodation of both passenger and cargo traffic growth. Two-thirds of the commercial airplanes operating today are projected to be in operation 20 years from now.

In addition to travel demand and airline replacement/reallocation decisions, the 2020 fleet mix will also depend on future air travel network trends and the capacity of the airports and the air traffic system to handle increased air travel demand. Over the next twenty years, regional hubs are expected to strengthen and the importance of gateway hubs is expected to decline. An increase in the number of non-stop flights between new city pairs (fragmentation) is also projected, particularly in the North Pacific and Europe-Asia markets.

Table 2-3 shows the year 2000 and projected year 2020 commercial aircraft fleet mix by general aircraft size category. The fleet breakdown projected for 2020 is the final result of regional air travel demand forecasts, colored by Boeing's view of how markets will develop in the next twenty years.

The percentage of smaller regional jets in the fleet is projected to nearly double by 2020, while the twin-aisle jet percentage is projected to increase only slightly from 19% to 22%. Single-aisle jets and those in the "747 and larger" category are projected to make up 58% and 5% of the 2020 fleet respectively as compared to 66% and 7% in the year 2000 fleet.

Table 2-3. Year 2000 and projected year 2020 commercial aircraft fleets broken down by general aircraft size category.

Aircraft Size Category	Year 2000 Percentage of Total Aircraft	Year 2020 Percentage of Total Aircraft
Smaller Regional Jets	8%	15%
Single Aisle	66%	58%
Twin Aisle	19%	22%
747 and Larger	7%	5%

Table 2-4. Distribution by airplane seat category of the 2000 fleet and the forecast 2020 fleet.

Seat Category	Included Models	2000 Year End Units	2000 Year End Percent	2020 Year End Units	2020 Year End Percent
Single-aisle	F28, F70	1,206	8.3	4,981	15.1
Small and intermediate	Bac1-11				
regional jets	RJ70/RJ85;BAe146-100/200				
	Regional jets from Bombardier, Embraer, and Fairchild Dornier				
90-120 seats and large	727-100	2,804	19.3	3,889	11.8
regional jets	737-100/-200/-500/-600				
	717-200				
	DC-9, MD-87				
	F100				
	RJ100/BAe146-300				
	Caravelle				
	Concorde				
	A318				
	Regional jets from Bombardier, Embraer, and Fairchild Dornier				
121-170 seats	737-300/-400/-700/-800	5,401	37.1	11,268	34.2
	727-200				
	720				
	A319/A320				
	Trident-3, Mercure				
	MD-81/-82/-83/-88/-90				
	DC-8-10/-20				
171-240 seats	737-900	1,407	9.7	3,907	11.9
	757				
	707-300B/C				
	A321				
	DC-8-30/-40/-50/-60/-70				
Twin-aisle	767	1,471	10.1	3,763	11.4
230-310 seats (2 class)	A300				
181-249 seats (3 class)	A310				
	A330-200				
311-399 seats (2 class)	777	1,231	8.5	3,451	10.5
250-368 seats (3 class)	A330-300				
	A340				
	L-1011				
	DC-10				
	MD-11				
Large	747	1,028	7.1	1,695	5.1
747 and larger (>400seats)	A380				
Totals		**14,548**	**100.0**	**32,954**	**100.0**

2.2.3 Airplane Assignments to Routes

The total projected demand for air travel in the year 2020 must be assigned to actual aircraft and routes in order to create a three-dimensional emissions inventory. For the purpose of forecasting turboprop and large jet airplane requirements, the 42 flows of Appendix A were consolidated into 26 major regional traffic flows

A detailed forecast of the fleet requirements of the airlines in each regional flow was created, using consolidated growth rates and a projected city-pair schedule derived from the schedules for 2000 published in the Official Airline Guide (OAG) a publication of OAG Worldwide. Individual city-pair service schedules for 2000 within each of the 26 traffic flow regions were grown to 2020 by the consolidated regional growth rate applicable for that region.

Specific airplane types were assigned to routes using a market share forecast model. These proprietary market share forecast methods take into account the market “fit” of each airplane type on each city-pair, assigning airplane types according to the total demand, forecast split between increasing frequency and increasing airplane size, city-pair range, and historical fleet trends of airlines serving the particular market. Table 2-4 above shows the distribution by airplane category of the 2000 jet fleet and of the forecast 2020 jet fleet.

A detailed forecast was not produced for the turboprop market. Instead, this market was projected for the year 2020 assuming that city-pairs not served by the smallest jet category will be served by turboprops.

The result of the airplane and route assignment task is a detailed city-pair level flight schedule by airplane type required to satisfy the forecast commercial passenger demand in 2020. This schedule was used to calculate the 3-dimensional emission inventory for 2020 commercial passenger service.

2.2.4 Airplane and Engine Assignment

In the city-pair level schedule first created using the Boeing Current Market Outlook forecast, some of the airplanes assigned to each flight were represented by a general airplane model (*e.g.*, 767). Specific information about the aircraft series (e.g., –300ER) was not specified. The engine type is not included in this initial schedule. These detailed data are necessary to more accurately calculate a 3-dimensional global emission scenario. The following describes the method used to add this data to the city pair level schedule:

Existing fleet data from the CASE2 fleet information database (purchased from Airclaims Limited) was used to project the distribution of those major airplane variants which are expected to still exist in the 2020 fleet. The specific airplane model/series/engine distribution for each of these airplane variants in 2020 was assumed to be the same as that produced between some base year and the end of the year 2000. The base year was determined by subtracting from 2020 the nominal retirement age assigned to the general airplane type being considered, 30 years for passenger, and 35 for freighters. This approach (based on the guidelines for retirement age given in Section 2.2.2) was applied both to current production airplanes for which continued growth was forecast and to out of production types that were expected to experience retirements from the fleet.

Production periods used to develop distributions for assigning specific airplane variants and engines to flights in the 2020 schedule for existing aircraft are given in Table 2-5 below.

Table 2-5 Airplane variant/engine distribution development assumptions for airplanes that were in production up through 2001.

Airplane Type	Production year span considered for determining airplane variant/engine distribution
Passenger Airplane	That of passenger airplane types within the series produced from 1990 to 2001
Freighter and Freighter conversions	That of freighter *and* passenger airplane types within the series produced from 1986 to 2001

There were some airplane series still appearing in the year 2020 schedule that ceased production before 1990 (passenger airplane) or 1986 (freighter). For these airplane series, the airplane variant/engine type distribution was determined using production data from the years shown in Table 2-6 to the end of their respective production run.

Table 2-6 Airplane variant/engine distribution development assumptions for passenger airplanes that ceased production by 1990 and freighters/conversions that ceased production by 1986.

Airplane Series	Production year span considered for determining airplane variant/engine distribution
DC9	1980 to end of production
727	1980 to end of production
L-1011	1980 to end of production
A300-B2/-B4	1980 to end of production
DC8	1971 to end of production
DC10	1980 to end of production
737 (JT8D Powered)	1985 to end of production
747-200/-300	1985 to end of production
Fokker 28	1985 to end of production
TU-134	1985 to end of production

The future engine distribution of an airplane type in production in 2001 was assumed to remain the same as that of pre-2001 production. Given that projections of specific engine distributions on future production airplanes were not available, this was the most reasonable assumption that could be made.

The enforcement of different emissions standards and/or emissions-related landing charges and fees in different parts of the world between now and 2020 may create a geographic bias in the global distribution of engine types over the fleet. The evolution of emissions-related standards and fees around the world between now and 2020 is not possible to predict with any certainty. Because of this, geographic bias in the global distribution of engine types was not considered in this work.

For airplane types not in production before 2001, the engine assigned was the same as the one assumed in the performance data provided by the Boeing Product Development (PD) Aerodynamics Group. No attempt was made to differentiate between engines that might be produced by different manufacturers for the same type of airplane. In some cases, emissions improvements were assumed for these airplane types

2.3 Technology Projections

2.3.1 Aircraft Performance

Airplane fuel efficiency improvements occur through reduction of airplane weight and drag and reducing engine specific fuel consumption (SFC). Once a specific airplane model-variant is introduced into service, further improvements in fuel efficiency are primarily due to engine SFC improvements. A notable exception to this trend is the introduction of winglets on some members of the 737 Next Generation family of aircraft. In the past, post entry-into-service improvements to a given airplane model have increased fuel efficiency by as much as 5 percent, but typically, these improvements increase airplane fuel efficiency by 1 to 2 percent.

It was assumed that the greatest improvements in the fuel efficiency of the 2020 fleet would result from the introduction of all new airplane types, rather than from incremental improvements to the existing airplanes and their variants. Experience with the development histories of past and present Boeing airplanes in response to market conditions was used to decide which market segments in 2020 would be served by all new airplane types, improved versions of present airplanes, or present airplanes as now defined. The improvement in fuel efficiency of a new airplane type was assumed to be 10% relative to the airplanes now serving that market segment. New airplane types were modeled by factoring the climb and cruise fuel mileage and emissions characteristics of existing airplanes.

Airplane/engine combinations in the 2020 fleet that were not in production before or at the time of this study were modeled using projected performance data obtained by building on the performance characteristics of current production aircraft.

2.3.2 Engine Emission Characteristics

All of the emission engines (engine combustor characteristic) assigned to aircraft in the projected 2020 fleet for this study were either in production or under the final stages of development at the time the assignments were made. Factors considered with assigning specific emission characteristics to the aircraft/engine combinations included cost, maintenance of airline fleet commonality and likely market and political forces that would drive the introduction of new engine technology into the fleet.

Emissions data used for all current production engines are based on that published in the ICAO Emissions Database (ICAO, 2002). Proprietary engine manufacturer emissions data were utilized for a few engines for which certification is imminent. For cases where no data were available for a specific type that is yet to be certified, a substitution of a similar-sized engine was made.

In the cases where a low emissions derivative version of an engine was available or would be in the foreseeable future, a projection was made of its most likely market penetration into the 2020 fleet for each affected aircraft/engine combination. If the low emissions derivative engine was projected to be on the majority of aircraft represented by a particular aircraft/engine combination, it was assigned to that aircraft/engine combination. If not, the standard engine was assigned.

Currently, research and development work is being done under such programs as the European ANTLE program (http://europa.eu.int/comm/research/growth/aeronautics-days/pdf/posters/antle.pdf) and the NASA Ultra Efficient Engine Technology (UEET) Program (http://www.ueet.nasa.gov/) to develop advanced subsonic aircraft engines that will be more fuel efficient and have better emissions characteristics than the best aircraft engines currently in production. The goal of the NASA UEET program for example, is to promote the development of technology that will lead to aircraft engine designs that will be 8-10% more fuel efficient than current production engines and will have landing take-off cycle NOx emissions that will be 70% below the ICAO CAEP2 limit. The ANTLE program has similar goals.

By 2020, some percentage of the commercial aircraft fleet will likely have engines that utilize technologies currently being developed to meet the goals of the NASA and European advanced engine technology programs. It was assumed when making projections for this 2020 scenario that penetration of such technologies into the 2020 commercial fleet will be minimal. Several factors must be taken into account when trying to project this technology penetration. These include the time it will take to bring demonstrated technology to production worthiness, along with available opportunities for introduction via new airplane types/derivatives. It may well be worth revisiting these market penetration assumptions in next couple of years as these research programs further mature, and when examining scenarios for 2030 or beyond.

2.4 Calculation of Global Emissions

2.4.1 Airplane/Engine Performance Data Substitution

Boeing has performance data needed to calculate fuel use and emissions for a large number of turbojet and turbofan powered airplane types. For all Boeing models that were produced in the year 2002 and earlier, actual performance data based on flight tests was used. Predicted performance data based on competitive analysis was used to model most non-Boeing models that were produced in the year 2002 and earlier. Predictions of airplane performance made by Boeing Product Development were used to model post-2002 EIS (entry into service) aircraft types.

For a small number of the aircraft/engine combinations projected to be in the 2020 fleet, no actual or predicted performance data was available. In most of these cases, available performance data for aircraft having similar size were used to model the performance characteristics of these aircraft/engine combinations. Otherwise an existing aircraft was scaled to attempt to match the performance. Similar sized aircraft were used to represent the non-western built types, while a scaled regional jet was used to represent some small regional jet types.

As in previous NASA global emissions inventory studies, for purposes of modeling performance and emissions, all turboprop models were grouped into three categories- small, medium and large. The "small" category includes airplanes such as the DeHaviland Twin Otter, the "medium" category includes airplanes such as the DeHaviland Dash-8, and the "large" category includes airplanes such as the Fokker F-27 and F-50. No improvements in the emissions or performance characteristics of the turboprop aircraft from 1992 technology level were assumed in this study. The same performance and emissions files used to model turboprop aircraft for the 1992 emission inventory (Baughcum *et al.,* 1996a) were used in the current study

2.4.2 Airplane Mission Performance Calculation

Boeing proprietary performance data files were used to model all of the airplane/engine combinations listed in the projected year 2020 city-pair schedule. These data files provide tables of time, fuel consumed and distance flown as a function of airplane gross weight and altitude for climbout, climb, and descent conditions. They also provide tables of fuel mileage (nautical miles per pound of fuel consumed) as a function of gross weight, cruise Mach number and altitude for cruise conditions and tables of long range cruise Mach number vs. gross weight and altitude. Constant fuel burn rates for taxi-in, taxi-out and approach based on typical mission allowances are also included in these data files. These performance data files were generated using the proprietary Boeing Mission Analysis Program (BMAP), and each file covers the whole operating envelope of the airplane. Simple interpolation routines were used to obtain engine fuel flow for a given flight condition.

In developing the performance data used to model aircraft in the 2020 commercial aircraft fleet global emission inventory, certain simplifying assumptions were made about the conditions under which aircraft operate. These assumptions, which are listed below, lead to errors in the calculation of global aircraft fleet fuel use and emissions. These errors have been discussed in detail in previous work (Baughcum *et al.*, 1996a; Daggett *et al.*, 1999).

Performance Assumptions for the NASA 2020 commercial emission scenario calculations:

- No winds
- International Standard Atmosphere (ISA) temperatures and pressures
- Continuous climb cruise flight segment with typical westbound flight beginning and ending cruise altitudes
- 747-300F, 747-400F, 747XF, DC-10F, A340-300F, A340-600F, A380-800F, MD-11F, 777-200F were modeled using typical freighter cargo loads and OEWs
- Passenger to freighter conversion aircraft were modeled using passenger OEW and 70% max structural load factor
- Selected small freighter aircraft and 'combi' aircraft were modeled using passenger version at 70% passenger load factor
- Passenger aircraft were modeled assuming no cargo (Payload = passengers + baggage weight)
- Passenger aircraft were modeled using a 70% passenger load factor
- Passenger and baggage weight were assumed to be 200 lb/passenger for single aisle and 210 lb/passenger for wide body aircraft

- Boeing ”brochure assumptions” were used for Operating Empty Weight, Maximum Landing Weight, Maximum Zero Fuel Weight, etc.
- Fuel density of 6.75 lb/gallon and fuel energy content of 18,580 BTU/lb
- Direct great circle routes--no turns or air traffic control diversions
- Takeoff Gross Weights (TOGW) are calculated assuming city pairs are at sea level. Performance calculations assume origin and destination airports are at their respective actual airport altitudes.
- Optimum aircraft operating rules
- Engine and airframe performance at new airplane level

2.4.3 Calculation of Global Emissions

The primary emissions produced by the combustion of jet fuel are water vapor (H_2O) and carbon dioxide (CO_2). The emission levels of H_2O and CO_2 are determined by the fuel consumption and the fraction of hydrogen and carbon contained in the fuel. Results from a Boeing study of jet fuel properties measured from samples taken from airports around the world have yielded an average hydrogen content of 13.8% (Hadaller and Momenthy, 1989). Emissions of sulfur dioxide (SO_2) from aircraft engines are determined by the levels of sulfur compounds in the jet fuel. Although jet fuel specifications require sulfur levels below 0.3%, they are typically much lower than this in the fuel supply utilized by the world’s aircraft fleet. The Boeing measurements obtained an average sulfur content of 0.042% with 90% of the samples below 0.1% (Hadaller and Momenthy, 1989). These measurements are in the range of values reported in more recent fuel surveys (Hadaller *et al.*, 2000). Future sulfur levels are projected to drop to about 0.02% (Hadaller and Momenthy, 1993).

Aircraft engine emissions are characterized in terms of an emission index, which has units of grams of emission per kilogram of fuel consumed. Current and projected emission indices are summarized in Table 2-6, based on the analyses of Hadaller and Momenthy for commercial Jet A fuel.

Table 2-7. Recommended emission indices (in units of grams emission/kilogram fuel).

Emission	Emission Index
Carbon Dioxide (CO_2)	3155
Water (H_2O)	1237
Sulfur oxides (as SO_2)	0.8

Emissions of nitrogen oxides (NO_X), carbon monoxide (CO) and hydrocarbons from an aircraft engine vary in quantity according to the combustor conditions. Nitrogen oxides are produced in the high temperature regions of the combustor primarily through the oxidation of atmospheric nitrogen. Thus, the NO_X produced by an aircraft engine is sensitive to combustor pressure, temperature, flow rate, and geometry. The NO_X emission index varies with the power setting of the engine, being highest at high thrust conditions. By contrast, carbon monoxide and hydrocarbon emission indices are highest at low power settings where combustor temperatures and pressures are low and combustion is less efficient.

Nitrogen oxides consist of both nitric oxide (NO) and nitrogen dioxide (NO_2). For NO_x, the emission index [$EI(NO_x)$] is given as gram equivalent NO_2 to avoid ambiguity. Although hydrocarbon measurements of aircraft emissions by species have been made (Spicer *et al.,* 1992), only total hydrocarbon emissions are considered in this work.

For the majority of the engines considered in this study, emissions data from engine certification measurements (ICAO, 2002) were used to model emissions characteristics. In these measurements, emissions of nitrogen oxides (NOx), carbon monoxide (CO) and total hydrocarbons (HC) are measured at standard day sea level conditions at four power settings [7% (idle), 30% (approach), 85% (climbout) and 100% (takeoff)]. If the ICAO database did not contain a particular engine, the data for that engine were obtained from the engine manufacturer. This was done for the engines on the three sizes of turboprops considered as well as the engines on some of the post-2002 developed airplanes projected to appear in the year 2020 fleet.

In the global emissions calculations, each airplane/engine combination in the 2020 city-pair schedule is matched to both a performance engine and an emissions engine. Fuel flow is calculated using the performance data. Then the emissions are calculated using the fuel flow based technique discussed later in this section.

In most cases, the emissions engine used to model an airplane was the same as that used to calculate the performance. In some cases, performance data for the airplane model identified in the 2020 city-pair flight schedule were available but the engine assumed in the performance data was different than the engine identified in the schedule. In the majority of these cases, the basic engine type is matched but not the specific maximum take-off thrust rating (a 737-700/CFM56-7B20 airplane/engine combination listed in the OAG schedule might be modeled using 737-700/CFM56-7B18 performance data).

Boeing has developed an empirical method that allows the calculation of emissions for a wide variety of airplanes and a large number of missions. This method was described in detail previously (Baughcum *et al.*, 1996a, Appendix D) and is referred to as the Boeing Fuel Flow Method #2. In this method, emission indices measured during sea level static engine certification tests are correlated with engine fuel flow and then scaled for ambient temperature, pressure, flight Mach number and humidity in order to determine emissions at flight conditions.

All global emissions calculations were done using the GAEC (Global Atmospheric Emissions Code) described in Baughcum *et al.*, 1994; 1996a). The GAEC graphical user interface was used to associate airplane/engine combinations listed in the OAG airplane schedule with the performance and emissions data that were used to model them in the inventory calculation. Once these associations were made, the GAEC code was used to calculate a global emission inventory using OAG schedule data, performance data, emissions data, and airport location data.

For purposes of the emissions calculations, the Earth's atmosphere was divided into a grid of three-dimensional cells with dimensions of 1 degree of latitude by 1 degree of longitude by 1 kilometer in altitude, up to 22 kilometers.

3. Results

3.1 Overview

The fuel use, emissions and distance calculated for the commercial aircraft fleet for the year 2020 are summarized in Table 3-1. For comparison, the results of the NASA fleet emissions calculations for 1992 scheduled (Baughcum *et al.*, 1996a), 1992 unscheduled (Mortlock and van Alstyne, 1998), and 1999 scheduled traffic (Sutkus *et al.*, 2001) are included in Table 3-1. For comparison, results for the previously published 2015 studies (Baughcum *et al.*, 1998; Mortlock and van Alstyne, 1998) are also shown. Emissions from general aviation and military aircraft were not calculated in this work and are not included in Table 3-1.

Table 3-1. Global fuel use, emissions, distance and traffic for civil air traffic calculated for years 1992 and 1999, and projected for the years 2015 and 2020.

	Fuel (Mtonne/yr)	NOx (Mtonne/yr)	HC (Mtonne/yr)	CO (Mtonne/yr)	Distance (km/yr)
1992 Scheduled Air Traffic	94.59	1.23	0.19	0.50	1.75×10^{10}
1992 Charter	6.55	0.09	0.00	0.02	Unknown
1992 Former Soviet Union/China	8.75	0.06	0.03	0.15	Unknown
1992 Commercial Aviation	**109.87**	**1.38**	**0.23**	**0.67**	**Unknown**
1999 Scheduled including the Former Soviet Union	127.98	1.69	0.19	0.68	2.58×10^{10}
1999 Charter	Unknown	Unknown	Unknown	Unknown	Unknown
1999 Commercial Aviation	**Unknown**	**Unknown**	**Unknown**	**Unknown**	**Unknown**
2015 Scheduled	252.72	3.57	0.17	1.12	4.61×10^{10}
2015 Charter	13.50	0.19	0.01	0.05	Unknown
2015 Former Soviet Union	15.79	0.12	0.05	0.26	Unknown
2015 Commercial Aviation	**282.02**	**3.88**	**0.23**	**1.44**	**Unknown**
2020 Commercial Aviation	**347.40**	**4.89**	**0.23**	**1.39**	**7.44×10^{10}**

3.2 Geographical Distribution of Emissions

The geographical distribution of the NOx emissions for the projected 2020 commercial air traffic is shown in Figure 3-1. The top panel shows the emissions as a function of altitude and latitude, while the bottom panel shows the emissions as a function of latitude and longitude. Peak emissions are projected to occur over the United States, Europe, the North Atlantic flight corridor, the North Pacific, and the Far East.

The projected fuel use for 2020 is shown as a function of latitude in Figure 3-2. For comparison, a similar plot for 1999 scheduled air traffic is also shown. Most of the air traffic is expected to be in the Northern Hemisphere, primarily at mid-latitudes. Figure 3-3 shows the fraction of the year 2020 global fuel use occurring within each 1 degree latitude band, illustrating similar distributions to those of 1999.

The distribution of emissions as a function of altitude is shown in Figure 3-4. Peak fuel use and NOx emissions occur at cruise altitudes since most of the flight time occurs at those altitudes. Peak CO and hydrocarbon emissions occur during the landing/takeoff cycle during idle and taxi conditions where power settings are relatively low and the combustor is relatively inefficient.

The effective emission indices (integrated over latitude and longitude) for the commercial fleet are shown as a function of altitude in Figure 3-5.

The total fuel use and emissions for the 2020 commercial fleet as a function of altitude (summed over latitude and longitude) are tabulated in Table 3-2. Table 3-2 also shows the cumulative percentage of total fuel use and emissions as a function of altitude and the effective emission indices for NOx, HC, and CO.

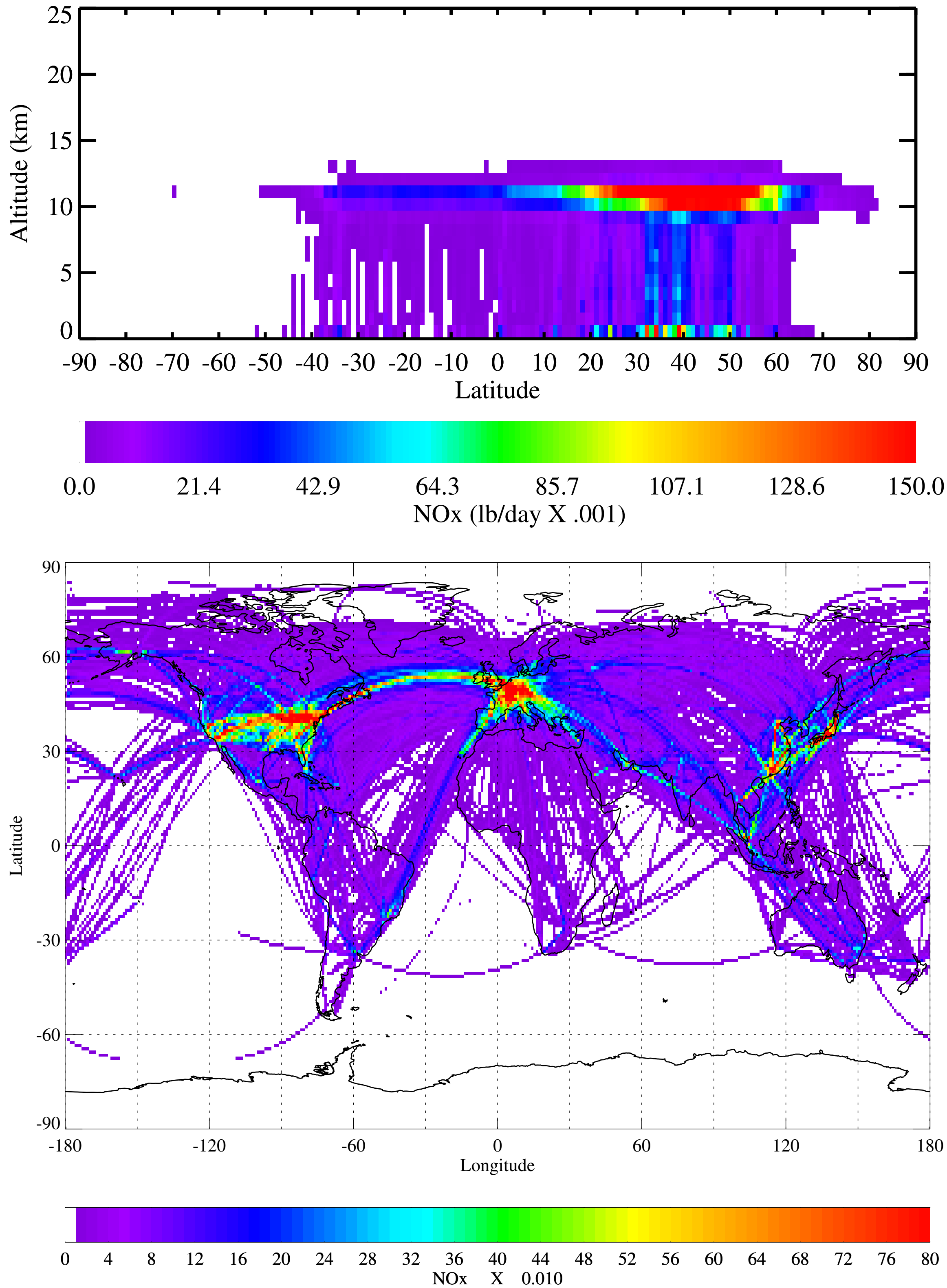

Figure 3-1. Geographical and altitude distribution of the NOx emissions for the projected 2020 commercial air traffic. Units of the lower plot are in pounds per day in each 1 degree latitude x 1 degree longitude grid box and integrated over 8-13 kilometers altitude.

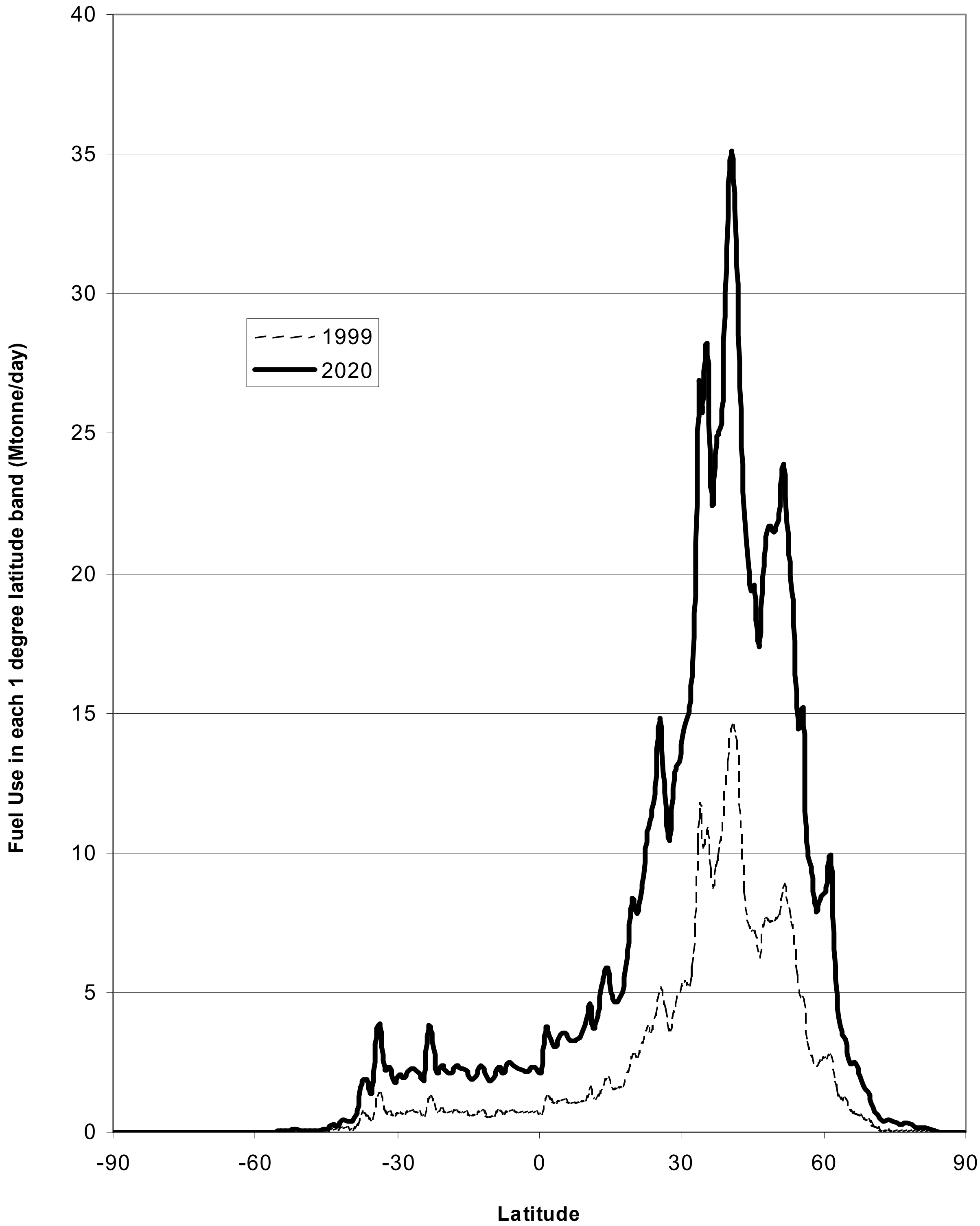

Figure 3-2. Commercial air traffic fuel use distribution as a function of latitude, comparing the 2020 scenario with that calculated for 1999 inventory.

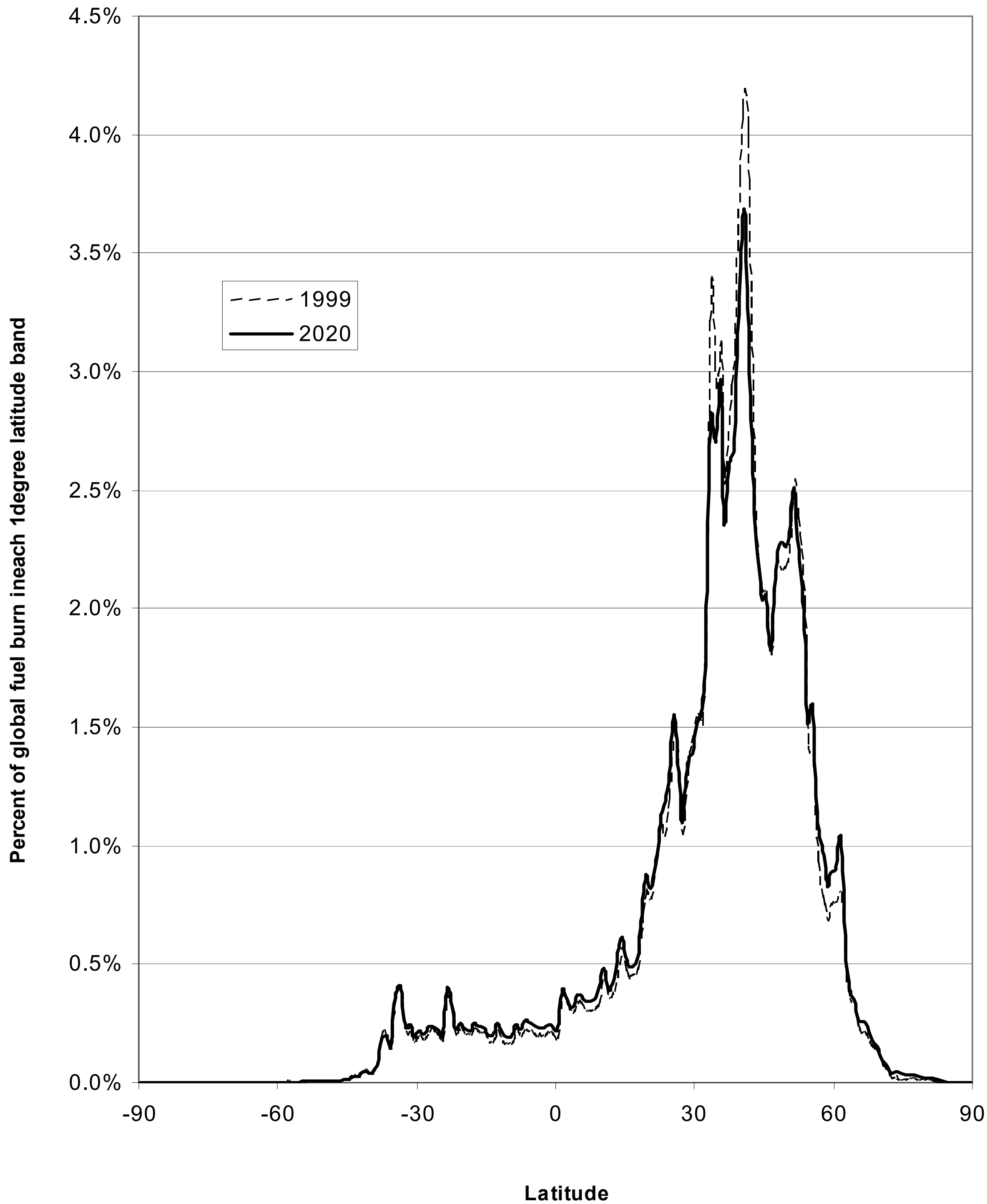

Figure 3-3. Fractional distribution of global fuel use as a function of latitude for the 2020 scenario and 1999 inventory.

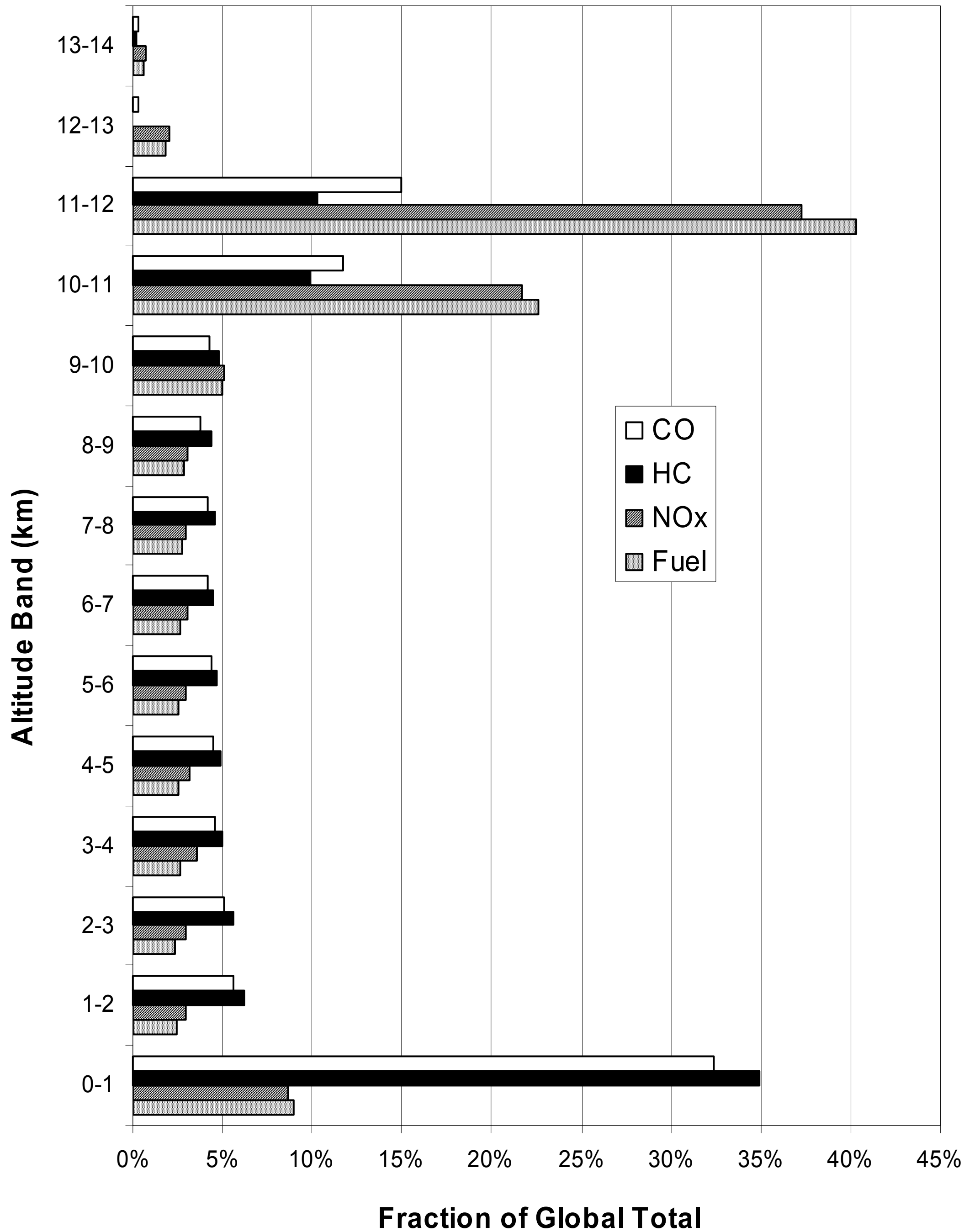

Figure 3-4. Emission distribution as a function of altitude for fuel used, NOx, hydrocarbons, and CO for the 2020 commercial fleet. The results are shown as the percent of the global total integrated over latitude and longitude for each emittant.

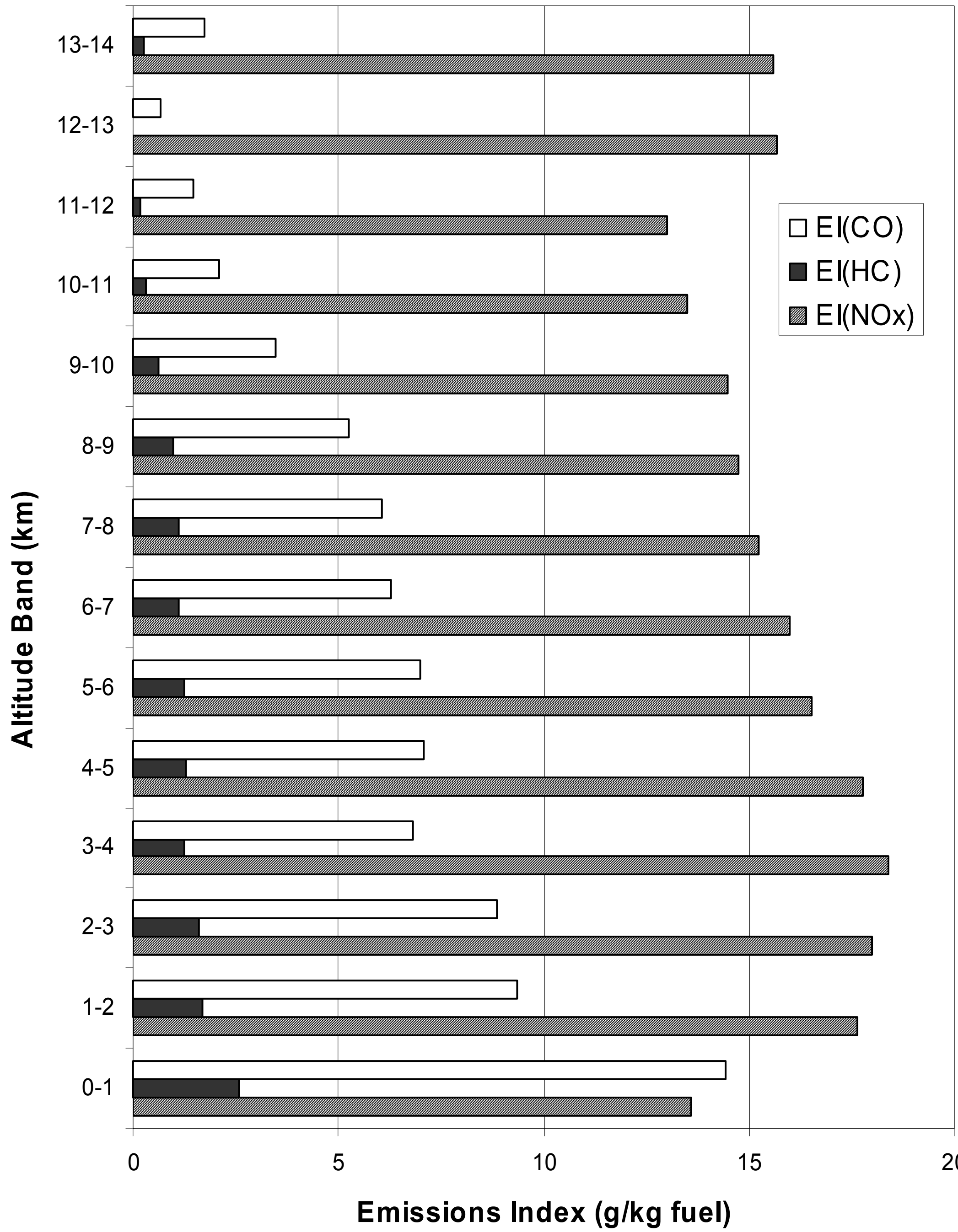

Figure 3-5. Effective emission indices as a function of altitude for the projected 2020 commercial fleet.

Table 3-2. Fuel use, emissions, cumulative fractions of fuel use and emissions, and effective emission indices as a function of altitude (summed over latitude and longitude) for commercial air traffic projected to 2020.

Altitude Band (km)	Fuel (kg/day)	Cum. Fuel (%)	NOx (kg/day)	Cum. NOx (%)	HC (kg/day)	Cum. HC (%)	CO (kg/day)	Cum. CO (%)	EI (NOx)	EI (HC)	EI (CO)
0-1	8.57E+07	9.0%	1.17E+06	8.7%	2.20E+05	34.9%	1.24E+06	32.4%	13.6	2.6	14.4
1-2	2.28E+07	11.4%	4.02E+05	11.7%	3.89E+04	41.1%	2.13E+05	38.0%	17.6	1.7	9.4
2-3	2.18E+07	13.7%	3.94E+05	14.6%	3.52E+04	46.6%	1.93E+05	43.0%	18.0	1.6	8.8
3-4	2.56E+07	16.4%	4.71E+05	18.1%	3.14E+04	51.6%	1.75E+05	47.6%	18.4	1.2	6.8
4-5	2.40E+07	18.9%	4.27E+05	21.3%	3.07E+04	56.5%	1.70E+05	52.0%	17.8	1.3	7.1
5-6	2.38E+07	21.4%	3.93E+05	24.3%	2.95E+04	61.2%	1.67E+05	56.4%	16.5	1.2	7.0
6-7	2.52E+07	24.1%	4.03E+05	27.3%	2.84E+04	65.7%	1.58E+05	60.6%	16.0	1.1	6.3
7-8	2.60E+07	26.8%	3.96E+05	30.2%	2.89E+04	70.3%	1.58E+05	64.7%	15.2	1.1	6.1
8-9	2.75E+07	29.7%	4.06E+05	33.2%	2.74E+04	74.6%	1.44E+05	68.5%	14.8	1.0	5.3
9-10	4.75E+07	34.7%	6.87E+05	38.4%	3.03E+04	79.4%	1.64E+05	72.8%	14.5	0.6	3.5
10-11	2.15E+08	57.3%	2.90E+06	60.0%	6.23E+04	89.3%	4.49E+05	84.5%	13.5	0.3	2.1
11-12	3.84E+08	97.6%	5.00E+06	97.3%	6.50E+04	99.6%	5.70E+05	99.4%	13.0	0.2	1.5
12-13	1.73E+07	99.4%	2.71E+05	99.3%	9.17E+02	99.8%	1.15E+04	99.7%	15.7	0.1	0.7
13-14	5.78E+06	100.0%	9.01E+04	100.0%	1.44E+03	100.0%	1.01E+04	100.0%	15.6	0.2	1.7
Global Total or Avg. EI	**9.52E+08**		**1.34E+07**		**6.30E+05**		**3.82E+06**		**15.7**	**1.0**	**5.8**

3.3 Distribution Among Aircraft Size Categories

The fuel use and emissions projected for 2020 for different airplane size classes are summarized in Table 3-3. The airplane size classes given in Table 3-3 are those defined in Table 2-4 of this report. The effective global emission indices projected for each of these size classes is tabulated in Table 3-4.

Table 3-3 shows that airplanes in the "311 to 399" seat class are projected to burn the largest percentage of fuel and produce the largest percentage of NOx in the year 2020 followed by airplanes in the "121 to 170" seat and "greater than 400" seat classes, reflecting the 2020 Boeing forecast view of fleet development and service patterns.

Table 3-3. Summary of year 2020 global fuel use and emissions by airplane size category**.**

Airplane Type and Size	Fuel (kg/day)	Fuel (%)	NOx (kg/day)	NOx (%)	HC (kg/day)	HC (%)	CO (kg/day)	CO (%)
Turboprops	8.9E+06	1%	9.2E+04	1%	4.1E+03	1%	4.1E+04	1%
Single aisle jets								
Regional Jets	5.1E+07	5%	4.5E+05	3%	2.4E+04	4%	2.6E+05	7%
91 to 120 seats	5.0E+07	5%	5.7E+05	4%	6.8E+04	11%	4.1E+05	11%
121 to 170 seats	2.0E+08	21%	2.4E+06	18%	1.3E+05	21%	1.1E+06	27%
171 to 240 seats	1.1E+08	12%	1.4E+06	10%	9.0E+04	14%	5.8E+05	15%
Twin aisle jets								
230 to 310 seats	1.4E+08	14%	1.9E+06	14%	1.2E+05	19%	5.3E+05	14%
311 to 399 seats	2.4E+08	25%	4.1E+06	30%	1.3E+05	21%	6.8E+05	18%
> 400 seats	1.6E+08	17%	2.5E+06	19%	6.5E+04	10%	2.7E+05	7%
Total	9.5E+08		1.3E+07		6.3E+05		3.8E+06	

Table 3-4. Summary of the globally averaged effective emission indices for 2020 commercial air traffic by airplane size category (Units of grams of emission/kilogram of fuel used).

Airplane Size	EI(NOx)	EI(HC)	EI(CO)
Turboprops	10.4	0.5	4.6
Single aisle jets			
Regional Jets	8.9	0.5	5.1
91 to 120 seats	11.5	1.4	8.2
121 to 170 seats	12.4	0.7	5.3
171 to 240 seats	12.0	0.8	5.1
Twin aisle jets			
230 to 310 seats	14.0	0.9	3.9
311 to 399 seats	17.0	0.5	2.9
> 400 seats	15.9	0.4	1.7

3.4 Comparison with Previous Inventories and Scenarios

A subsonic emission scenario of scheduled air traffic for the year 2015 was created and delivered to NASA in 1998 (Baughcum *et al.*, 1998). The methodology used to create this scenario was very similar to the one used to create the 2020 emission scenario documented in this report although the 2020 scenario now includes all commercial aviation. Mortlock and van Alstyne (1998) have published a scenario for 2015 charter traffic.

The main difference between the methodologies used to create these two scenarios is the future fleet projection upon which they are based. The 2015 scenario is based upon airplane traffic projections made in the Boeing 1996 Current Market Outlook (Boeing Commercial Airplane Group, 1996) and the 2020 scenario is based on traffic projections made in the Boeing 2001 CMO. Forces affecting world aircraft fleet development are constantly changing. Because of this, projections of future fleet development made in the 1996 CMO differ in some ways from those made in the 2001 CMO.

The fact that the 2015 and 2020 scenarios are based on slightly different views of the future makes it impossible to utilize the results of the two scenarios to establish a meaningful future trend. The year 2020 scenario is based on current Boeing technology and market projections. Factors that influence scenarios include projected airplane fleet mix, projected engine fleet mix, projected combustor mix, projected city pairs and frequencies, assessments of current and future levels of technology and performance for Boeing and competitor aircraft. All of these factors change with time, some more than others.

The calculated global fuel use by commercial civil aviation (not including general aviation or military) over the 1992 to 2020 time period is shown in Figure 3-6. It is not possible to calculate a trend because the published inventories/scenarios are not completely self-consistent and gaps exist. For 1992, scheduled air traffic (as listed in the Official Airline Guide) did not include charter flights or much domestic traffic in the Former Soviet Union and China. These were estimated by Mortlock and van Alstyne (1998). By 1999, most flights in the former Soviet Union and China and some (but not all) charter flights were listed in the OAG. No separate charter inventory was developed for 1999. The 2020 market forecast includes all traffic demand: scheduled traffic in the former Soviet Union, China, the rest of the world and all charter air traffic. This unfortunate lack of consistency in the content of emissions inventories, the result of changes in the available data, precludes calculating accurately the growth rates of fuel use and emissions.

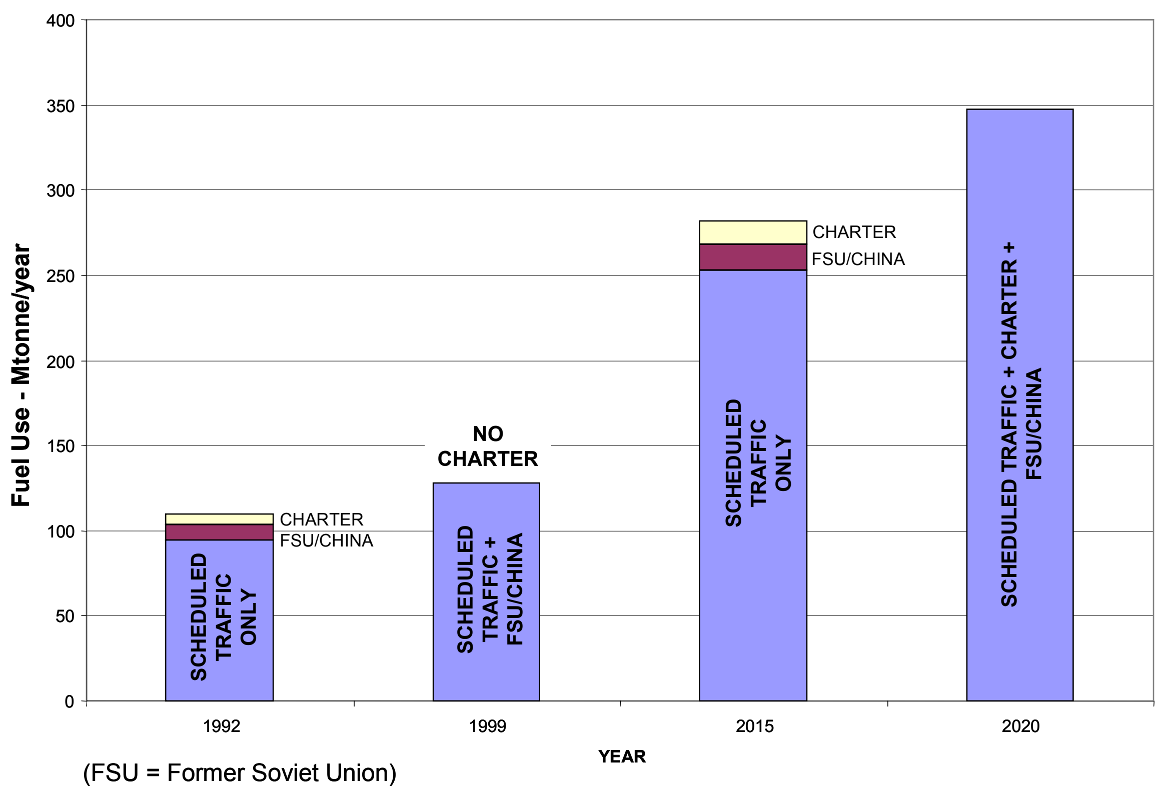

Figure 3-6. Annual fuel use by commercial civil aviation over the 1992 to 2020 time period.

Figure 3-7 Illustrates the differences in the distribution of fuel use with airplane size in the 2015 and 2020 inventories due to a changing view of the development of the market. The view of 2015 from 1996 was that large and very large airplanes would carry an increasing percentage of traffic as demand continued to grow. The view of 2020 from 2001 is that of a growing dominance of the “middle of the market” airplane size that combines long-range capability with frequency of service. Performance assumptions (capability and efficiency) for some types in the large airplane size class have also changed between the 2015 study and this study with the 2020 levels being more conservative in general and much more conservative for the 800 seat class.

Figures 3-8 and 3-9 give the altitude distributions for fuel use and NOx for the 2020 scenario documented in this work and the 2015 scenario generated previously (Baughcum *et al.*, 1998). The overall characteristics of the two altitude distributions are the same in that the majority of fuel use and NOx emissions occur at cruise altitudes in the 9 to 12 kilometer altitude band. For the 2020 scenario, fuel use and NOx emissions show a slight shift to higher altitudes.

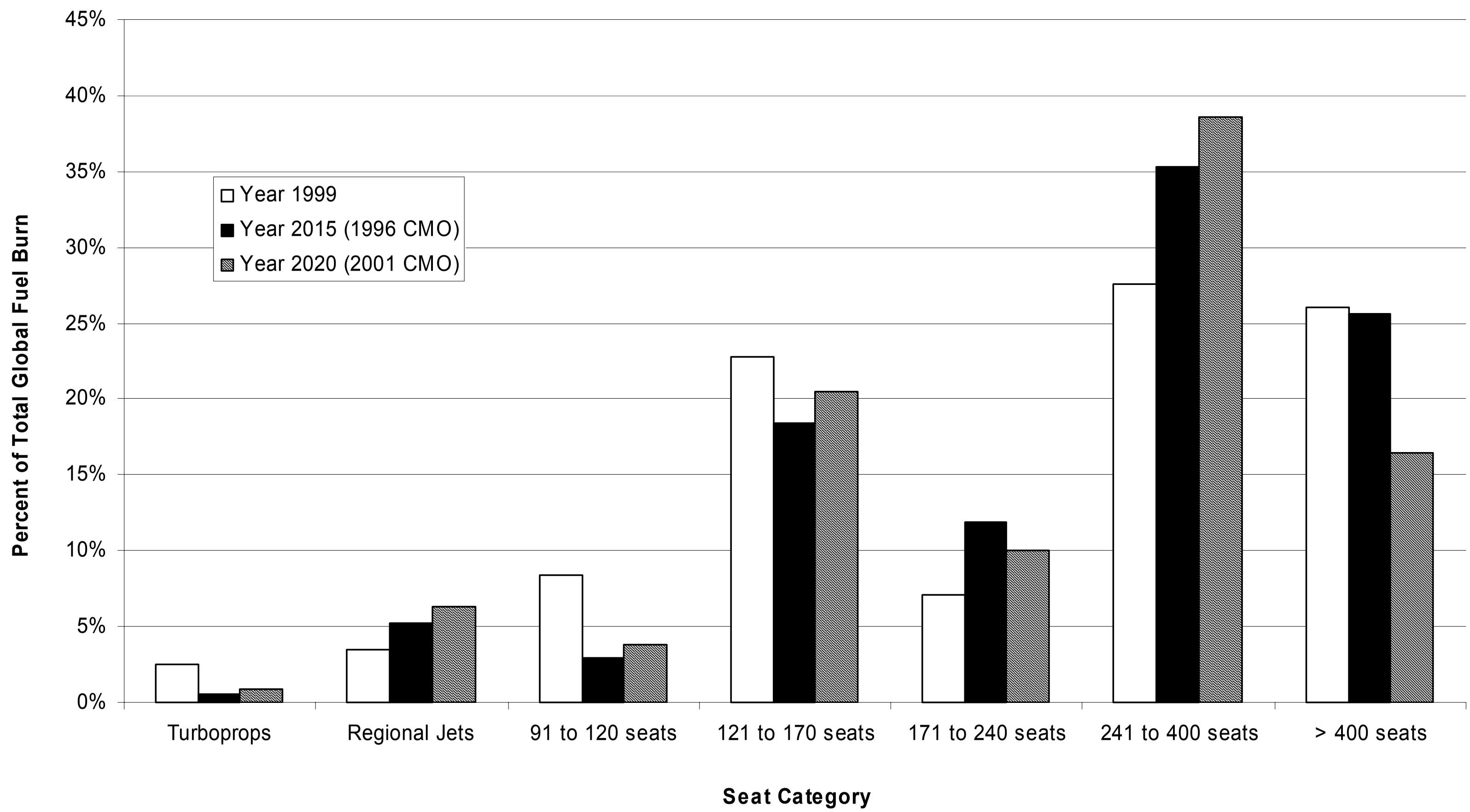

Figure 3-7. Commercial fleet fuel use distribution by airplane size class for the year 1999 and projected for 2015 and 2020

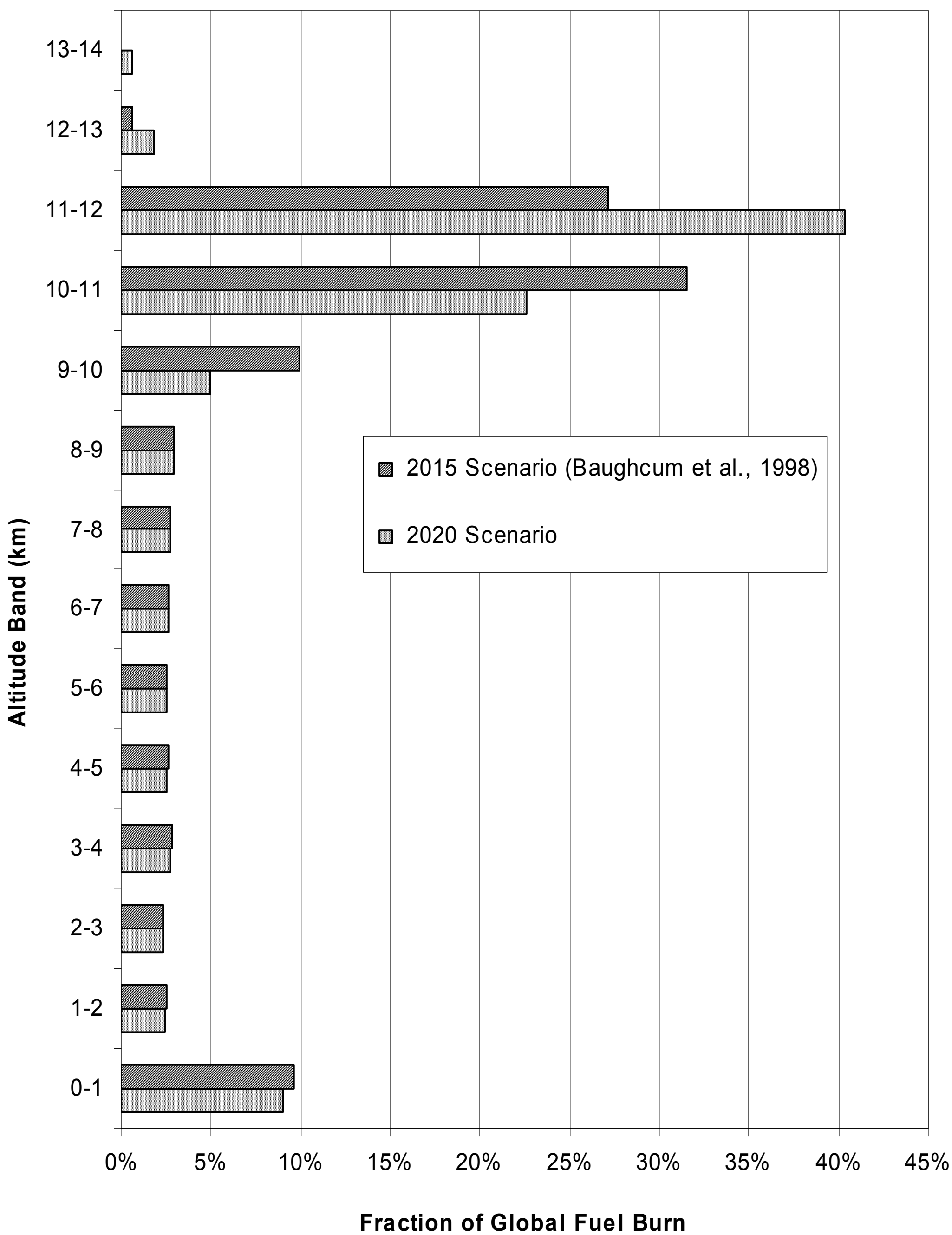

Figure 3-8. Comparison of the fuel consumption altitude distribution between 2020 and 2015 Scenarios

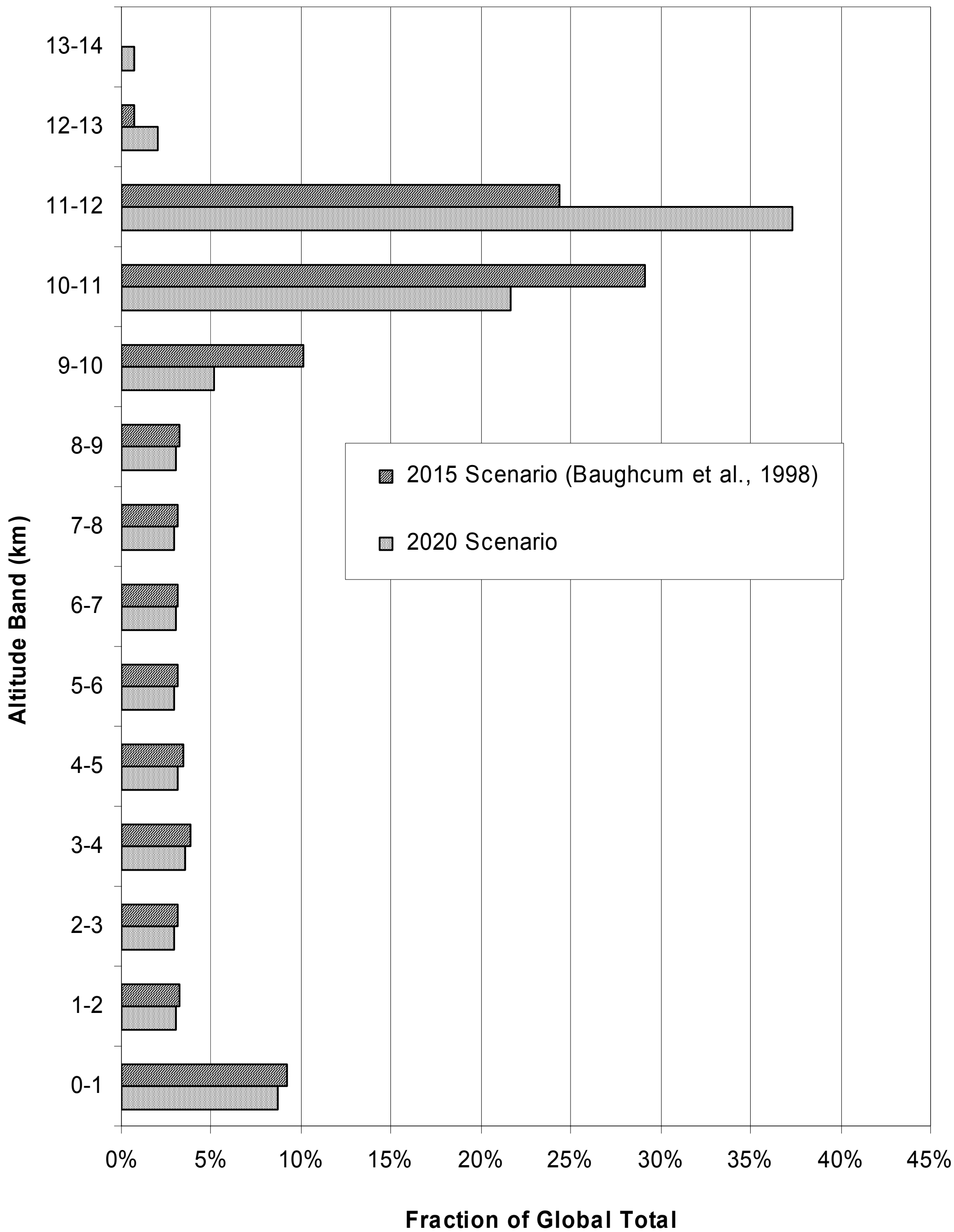

Figure 3-9. Comparison of the altitude distribution of NOx between 2020 and 2015 Scenarios.

Regional Growth in Air Traffic

Projections in future air traffic vary by geographical regions as was discussed earlier. Figure 3-10 shows the increase in fuel use at cruise altitudes (8-13 kilometers) between the 1999 scheduled aircraft emission inventory and the 2020. As discussed earlier, 1999 did not include charter traffic. Thus, some of the increase shown over Europe may be due to one database including charter while the reference year (1999) did not.

Figure 3-10 highlights that the largest increase in fuel use and emissions is expected to occur in the well-developed markets (United States and Europe) and the rapidly growing markets of China and East Asia.

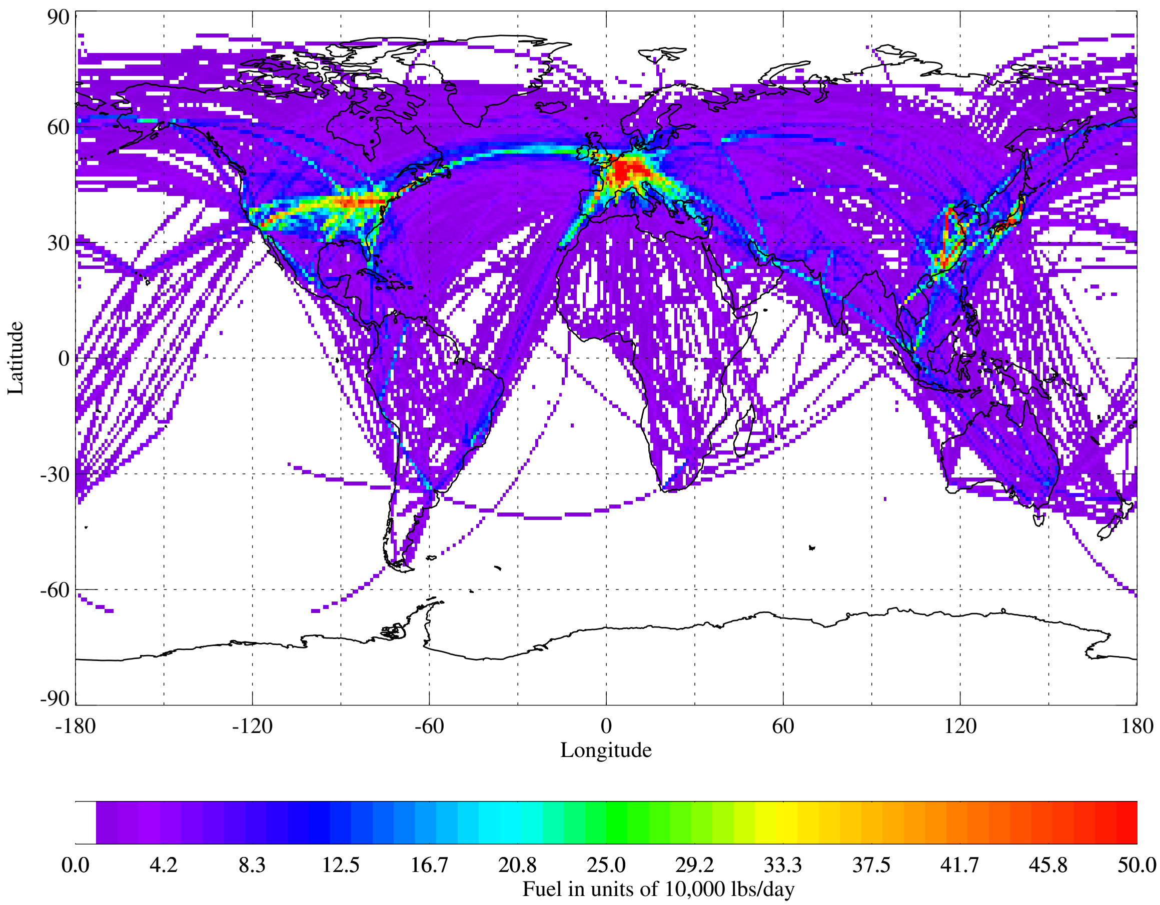

Figure 3-10. The increase in cruise fuel use between 1999 and 2020, integrated over the 8-13 kilometer altitude band.

To highlight the regional growth in air traffic, Figures 3-11 to 3-13 show ratios of cruise fuel use in 2020 relative to 1999. By choosing a threshold to consider, we can separate the analysis for mature versus emerging markets. In Figure 3-11, only grid cells where the integrated cruise fuel use (over the 8-13 kilometer altitude band) was greater than 100,000 pounds/day in a 1 degree latitude x 1 degree longitude box in 1999 are shown. Figure 3-12 is a similar plot but the threshold was 50,000 pounds/day. Figure 3-13 shows the results for a threshold of 10,000 pounds/day.

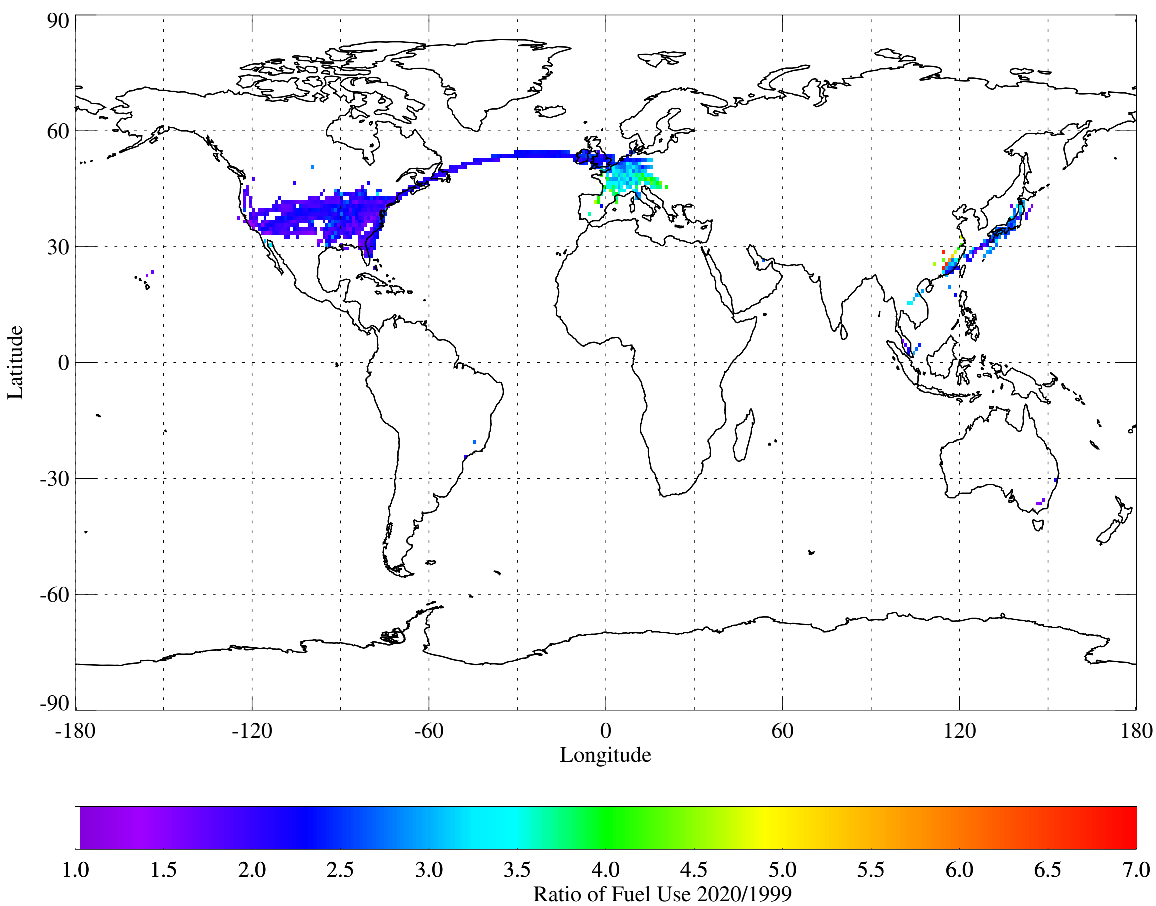

Figure 3-11. Ratio of Fuel Use in 2020 to 1999 for locations with at least 100,000 pounds of cruise fuel use/day in 1999.

As shown in Figure 3-11, the growth in the heavily traveled region is a factor of about 2 to 3.5 between 1999 and 2020. Figure 3-12 and 3-13 show that traffic increases at a higher rate in some of the less dense regions, particularly China.

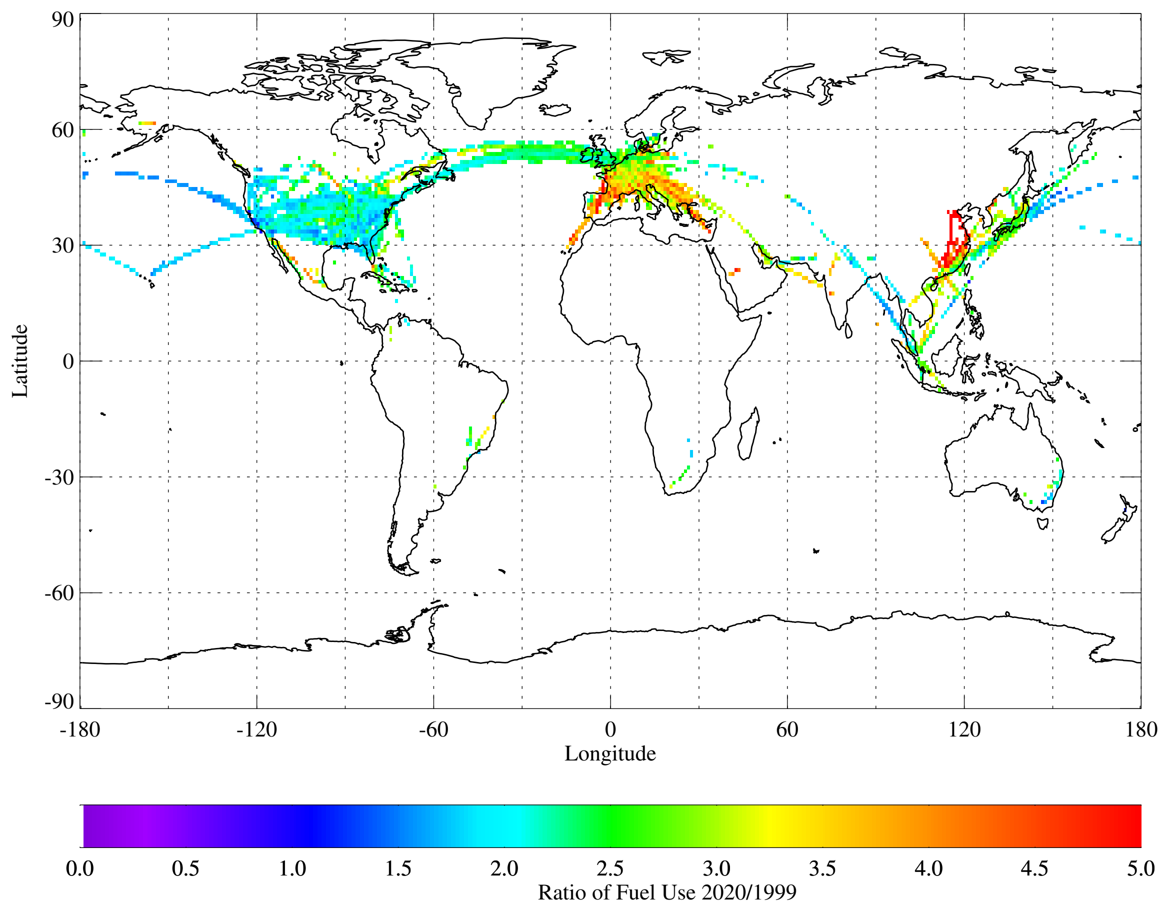

Figure 3-12. Ratio of Fuel Use in 2020 to 1999 for locations with at least 50,000 pounds of cruise fuel use/day in 1999.

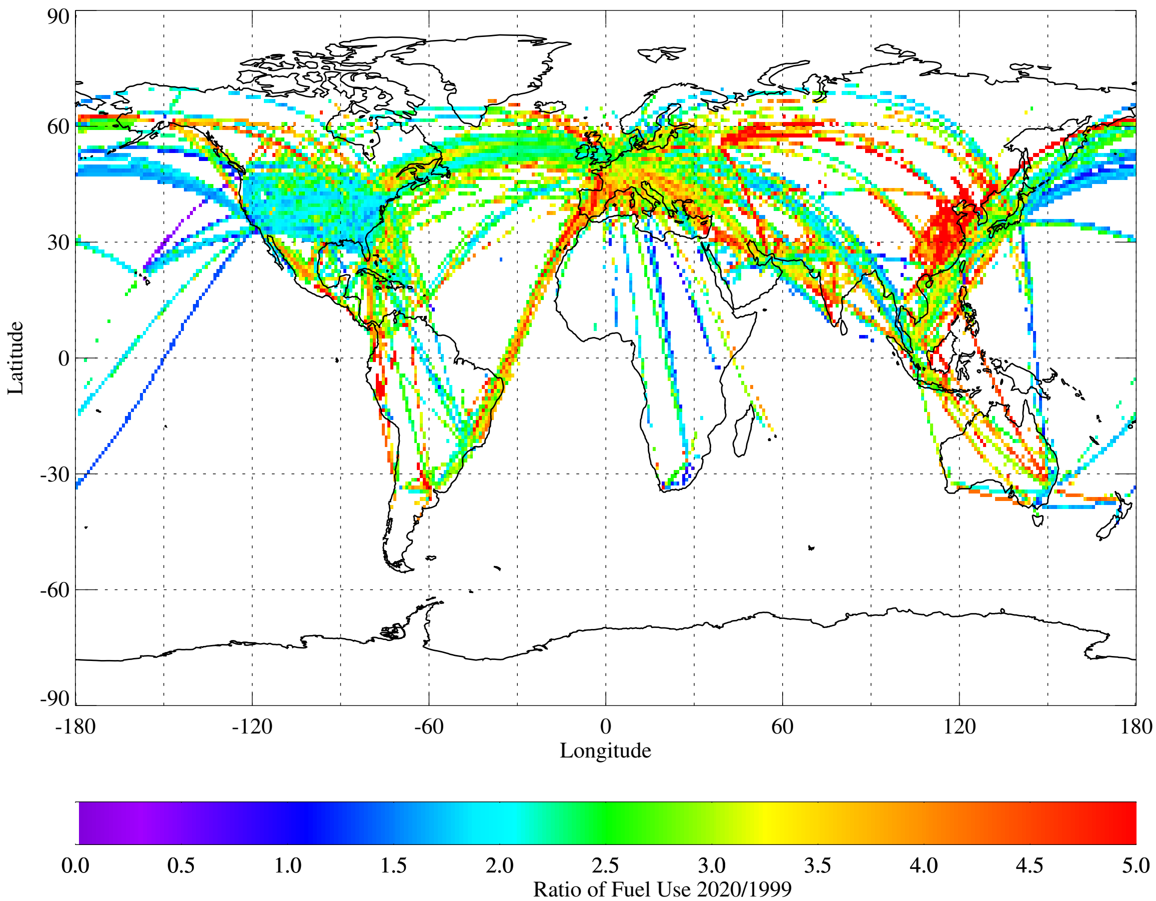

Figure 3-13. Ratio of Fuel Use in 2020 to 1999 for locations with at least 10,000 pounds of cruise fuel use/day in 1999.

3.5 Database Availability

The 3-dimensional commercial aircraft emission scenario of fuel use and emissions calculated on a 1 degree latitude x 1 degree longitude x 1 km altitude grid for the year 2020 has been delivered in electronic format to the NASA Glenn Research Center. Questions concerning the availability of these data should be directed to Dr. Chowen C. Wey (Chowen.C.Wey@grc.nasa.gov), the NASA GRC contract monitor for this work. Technical questions about the data set should be sent to Steven L. Baughcum (Steven.L.Baughcum@boeing.com) at the Boeing Company, P. O. Box 3707, MS 0R-RC, Seattle, WA 98124-2207.

4. Summary and Conclusions

This report describes the development of three-dimensional inventories of aircraft fuel use and emissions (NOx, CO, and hydrocarbons) from commercial air traffic projected to the year 2020. The data are on a 1° latitude x 1° longitude x 1 km altitude grid. This emission scenario was developed for the NASA Ultra Efficient Engine Technology (UEET) Program under contract NAS3-01140, Task Assignment 5. It will be available for use by atmospheric scientists conducting modeling studies on the atmospheric effects of aviation, including the NASA Global Modeling Initiative (GMI).

Emissions produced by the world's entire aircraft fleet come from scheduled, charter, military, and general aviation air traffic. In this report, we present the results and methodology used for the calculation of emissions from commercial air traffic which includes both the scheduled and charter portions of flight operations by turboprop, passenger jet, and cargo jet aircraft. Forecast charter traffic is allocated to the appropriate routes in this scenario.

Comparisons of the 2020 emissions inventory with the 1999 inventory (Sutkus *et al.*, 2001) provide a means of judging the relative growth of fuel consumption, NOx emissions and traffic demand. Adjustments to the 1999 inventory are required to make such comparisons due to the fact that different portions of the world aircraft fleet were considered in each case. Table 4-1 shows a comparison between 2020 scenario results and 1999 adjusted inventory results. These results show that fuel consumption is expected to grow more slowly than traffic demand and NOx emissions more rapidly. This reflects some assumptions of projected city pair and traffic growth, new aircraft penetration, fleet retirements, airplane efficiency improvements and combustor technology. These projections continuously evolve over time, with airplane sizes, city pairs, frequencies, new and retiring airplane market forecasts, technology developments all subject to change. It is recommended that a new 20-year look ahead scenario be conducted at least every 5 years.

Table 4-1 Comparison of 2020 and 1999 emissions inventory results

	World Passenger Traffic Demand (Billion RPK)	**Calculated Fuel Usage (kg/year)**	**Calculated NOx Emissions (kg/year)**
1999 Inventory as calculated [1]	N/A	1.28×10^{11}	1.69×10^{9}
1999 Adjusted Inventory [2]	3,170	1.34×10^{11}	1.77×10^{9}
2020 Inventory [3]	8,390	3.47×10^{11}	4.89×10^{9}
Ratio 2020/1999 Adjusted	2.65	2.58	2.76

[1] The 1999 emissions inventory as calculated (Sutkus *et al.*, 2001) included scheduled passenger and freighter flights as contained in the Official Airline Guide (OAG), but no charter flights.

[2] The 1999 emissions inventory adjusted to include charter flights (assuming charter comprises ~5% of world traffic, and that charter aircraft have the same fuel efficiency and NOx characteristics as scheduled aircraft.

[3] The 2020 emissions inventory includes forecast scheduled passenger and freighter flights, as well as all forecast charter traffic allocated to appropriate scheduled routes.

The 3-dimensional commercial aircraft emission scenario of fuel use and emissions for the year 2020 has been delivered in electronic format to the NASA Glenn Research Center.

APPENDIX A: WORLD TRAFFIC BY REGIONAL FLOW, RPKS IN BILLIONS

Regional Flow	1985	1990	1995	1996	1997	1998
Africa--Africa	13.540	14.689	14.775	15.335	16.578	17.340
Africa--Europe	43.037	47.732	57.178	66.897	75.259	79.248
Africa--Middle East	5.156	7.394	6.479	6.973	7.490	8.187
Africa--North America	1.220	1.298	2.640	3.126	4.599	4.201
Central America--Central America	12.820	14.306	18.267	17.858	18.409	19.440
Central America--Europe	17.868	27.647	44.193	47.507	51.720	56.737
Central America--North America	43.339	63.714	71.097	74.580	76.539	80.835
Central America--South America	3.287	3.499	4.271	4.595	5.269	6.608
China--China	8.436	18.254	56.624	61.156	61.679	62.468
China--Europe	9.577	16.927	26.611	29.352	32.407	34.157
China--North America	7.807	13.434	21.630	24.143	27.094	29.670
China--Northeast Asia	6.754	10.916	15.998	17.343	18.037	16.738
China--Oceania	3.002	5.810	9.234	10.674	11.102	11.435
China--Southeast Asia	8.081	14.489	23.032	27.200	28.532	26.764
CIS Region--CIS Region	175.814	224.240	63.395	50.764	44.489	38.704
CIS Region--International	15.863	24.098	33.918	39.483	42.595	44.511
Europe--Europe	170.048	258.346	306.836	324.374	347.578	378.055
Europe--Middle East	43.436	41.512	44.920	47.897	51.861	54.869
Europe--North America	158.599	230.688	278.895	296.434	324.061	351.578
Europe--Northeast Asia	17.025	29.347	46.550	54.561	58.381	59.665
Europe--South America	12.250	22.309	32.930	37.211	40.262	46.260
Europe--Southeast Asia	26.600	46.386	65.884	72.032	81.483	82.868
Europe--Southwest Asia	11.859	17.470	20.666	23.353	22.697	24.354
Middle East--Middle East	17.685	19.462	20.713	21.789	22.373	23.871
Middle East--North America	5.012	6.560	10.309	11.258	10.581	12.454
Middle East--Southeast Asia	15.136	10.980	20.584	20.442	20.832	20.061
Middle East--Southwest Asia	14.505	16.583	23.194	23.762	24.261	25.934
North America--North America	470.633	589.055	670.470	721.958	758.000	781.491
North America--Northeast Asia	46.880	95.162	121.512	129.111	139.994	129.993
North America--Oceania	11.008	18.972	24.135	24.820	24.996	25.067
North America--South America	14.460	19.615	35.885	38.339	43.015	46.217
North America--Southeast Asia	8.013	15.324	25.886	25.981	30.705	28.540
Northeast Asia--Northeast Asia	32.273	50.016	67.404	71.708	75.382	74.353
Northeast Asia--Oceania	6.055	12.879	31.823	35.322	36.383	25.322
Northeast Asia--Southeast Asia	15.998	32.512	44.335	47.832	50.703	45.734
Oceania--Oceania	18.614	26.241	42.671	44.547	45.808	46.511
Oceania--South America	0.115	0.688	0.641	0.757	0.756	1.020
Oceania--Southeast Asia	12.233	24.286	33.065	36.769	38.936	36.989
South America--South America	29.477	33.841	39.670	42.248	46.600	51.959
Southeast Asia--Southeast Asia	17.665	29.881	53.811	58.223	61.136	48.909
Southeast Asia--Southwest Asia	5.658	5.804	8.104	8.873	9.540	9.588
Southwest Asia--Southwest Asia	10.471	11.602	15.205	16.117	16.130	15.775
Rest of World	5.848	7.534	11.776	15.046	15.449	14.726
World Total	**1573.158**	**2181.501**	**2567.213**	**2747.755**	**2919.698**	**2999.208**

	1999	2000	2010	2020	2001-2010 %/year	2001-2020 %/year
Regional Flows						
Africa--Africa	18.034	19.422	32.957	53.338	5.4	5.2
Africa--Europe	88.362	99.407	159.141	248.490	4.8	4.7
Africa--Middle East	8.760	9.811	14.832	21.997	4.2	4.1
Africa--North America	4.407	4.416	7.273	10.444	5.1	4.4
Central America--Central America	21.384	23.950	48.128	90.493	7.2	6.9
Central America--Europe	61.162	66.361	99.077	150.257	4.1	4.2
Central America--North America	86.493	93.931	140.336	215.549	4.1	4.2
Central America--South America	6.046	7.256	12.399	21.989	5.5	5.7
China--China	64.030	71.073	196.572	419.037	10.7	9.3
China--Europe	37.470	40.093	67.947	111.253	5.4	5.2
China--North America	30.857	33.171	57.201	117.262	5.6	6.5
China--Northeast Asia	17.508	19.434	38.337	71.427	7.0	6.7
China--Oceania	11.263	12.130	17.224	24.043	3.6	3.5
China--Southeast Asia	27.208	29.330	48.424	79.167	5.1	5.1
CIS Region--CIS Region	39.363	37.001	58.933	94.875	4.8	4.8
CIS Region--International	42.063	42.274	78.268	130.807	6.4	5.8
Europe--Europe	406.063	440.578	696.839	1097.096	4.7	4.7
Europe--Middle East	59.643	65.011	98.214	147.098	4.2	4.2
Europe--North America	380.055	419.961	593.154	856.858	3.5	3.6
Europe--Northeast Asia	60.559	63.587	114.361	195.171	6.0	5.8
Europe--South America	51.118	53.162	96.371	164.349	6.1	5.8
Europe--Southeast Asia	89.912	95.756	156.690	243.267	5.0	4.8
Europe--Southwest Asia	24.719	26.227	47.262	83.809	6.1	6.0
Middle East--Middle East	25.303	27.834	41.333	64.107	4.0	4.3
Middle East--North America	14.333	16.053	23.139	33.041	3.7	3.7
Middle East--Southeast Asia	21.586	23.960	33.171	48.015	3.3	3.5
Middle East--Southwest Asia	27.490	29.414	48.041	78.458	5.0	5.0
North America--North America	823.969	858.576	1128.591	1595.199	2.8	3.1
North America--Northeast Asia	137.402	140.150	220.551	325.568	4.6	4.3
North America--Oceania	26.861	29.950	42.222	63.204	3.5	3.8
North America--South America	45.431	44.750	84.483	141.211	6.6	5.9
North America--Southeast Asia	31.422	32.050	52.496	93.515	5.1	5.5
Northeast Asia--Northeast Asia	77.104	78.646	142.416	288.159	6.1	6.7
Northeast Asia--Oceania	22.284	24.066	45.856	66.458	6.7	5.2
Northeast Asia--Southeast Asia	46.649	48.515	90.157	161.242	6.4	6.2
Oceania--Oceania	47.441	49.244	63.415	81.891	2.6	2.6
Oceania--South America	1.275	1.282	2.169	3.456	5.4	5.1
Oceania--Southeast Asia	41.613	46.190	64.837	94.511	3.4	3.6
South America--South America	52.218	50.913	127.626	250.916	9.6	8.3
Southeast Asia--Southeast Asia	50.376	53.650	104.675	187.068	6.9	6.4
Southeast Asia--Southwest Asia	10.355	10.935	20.192	37.167	6.3	6.3
Southwest Asia--Southwest Asia	15.696	16.010	38.787	84.866	9.3	8.7
Rest of World	14.715	16.054	27.276	43.728	5.4	5.1
World Total	**3170.003**	**3371.586**	**5281.370**	**8389.858**	**4.6**	**4.7**

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	May 2003	Final Contractor Report

4. TITLE AND SUBTITLE

Commercial Aircraft Emission Scenario for 2020: Database Development and Analysis

5. FUNDING NUMBERS

WBS–22–714–01–14
NAS3–01140, Task 5

6. AUTHOR(S)

Donald J. Sutkus, Jr., Steven L. Baughcum, and Douglas P. DuBois

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Boeing Commercial Airplane Group
P.O. Box 3707
Seattle, Washington 98124

8. PERFORMING ORGANIZATION REPORT NUMBER

E–13926

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA CR—2003-212331

11. SUPPLEMENTARY NOTES

Project Manager, Chowen C. Wey, Vehicle Technology Directorate, NASA Glenn Research Center, organization code 0300, 216–433–8357.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Categories: 01 and 03 Distribution: Nonstandard

Available electronically at http://gltrs.grc.nasa.gov

This publication is available from the NASA Center for AeroSpace Information, 301–621–0390.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

This report describes the development of a three-dimensional database of aircraft fuel use and emissions (NOx, CO, and hydrocarbons) for the commercial aircraft fleet projected to 2020. Global totals of emissions and fuel burn for 2020 are compared to global totals from previous aircraft emission scenario calculations.

14. SUBJECT TERMS

Aircraft emissions; Emission inventory; Atmospheric impact

15. NUMBER OF PAGES

55

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	